UNIVERSITY OF RIJEKA
FACULTY OF CIVIL ENGINEERING

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MODEL FOR EROSION INTENSITY AND SEDIMENT PRODUCTION ASSESSMENT BASED ON EROSION POTENTIAL METHOD MODIFICATION

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Doctoral thesis

Supervisor: Assoc. Prof. Barbara Karleuša, PhD

Co-supervisor: Prof. Nevenka Ožanić, PhD

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SVEUČILIŠTE U RIJECI
GRAĐEVINSKI FAKULTET

Nevena Dragičević

MODEL ZA PROCJENU INTENZITETA I PRODUKCIJE EROZIJSKOG NANOSA MODIFIKACIJOM METODE POTENCIJALA EROZIJE

Doktorski rad

Mentor: Izv.prof.dr.sc. Barbara Karleuša

Komentor: Prof.dr.sc. Nevenka Ožanić

Rijeka, 2016

Mentor rada: Izv.prof.dr.sc. Barbara Karleuša

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Doktorski rad obranjen je dana ________________________________ u Rijeci pred povjerenstvom u sastavu:

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ZAHVALA

Najveću zahvalnost za svu potporu, razumijevanje i strpljenje dugujem svojoj obitelj, suprugu Danielu i mojim dvjema curama Eleni i Leoni. Ovaj doktorat posvećujem svojim roditeljima, koji su moja velika potpora. Hvala im na svoj ljubavi, savjetima i smjernicama koje su mi kroz život dali te svoj potpori i pomoći za vrijeme doktorata. Hvala jednim i drugim nonićima na razumijevanju i pomoći oko cura za vrijeme cijelog doktorskog studija, a naročito za vrijeme boravka u Lancasteru i pred kraj doktorata.

Posebnu zahvalnost dugujem svojoj mentorici izv.prof. Barbari Karleuši i komentorici prof. Nevenki Ožanić na svoj potpori i pomoći koju su mi pružile kroz cijeli doktorski studij, a posebno za vrijeme istraživanja i samog pisanja doktorata. Profesorici Barbari Karleuši hvala na svom izdvojenom vremenu posebno u zadnjih godinu dana čija pomoć je bila neprocjenjiva. Veliko hvala prof. Kisiću na svim savjetima u fazi pripreme i za vrijeme provedbe mjerenja na terenu, te suprugu Danielu koji je bio moja desna ruka na terenu. Također se moram zahvaliti profesoru Duncanu Whyattu i Gemmi Davies na ukazanom strpljenju, prenesenom znanju i svim savjetima za vrijeme boravka na sveučilištu u Lancasteru, koji je obilježio moj daljnji smjer istraživanja u doktorskom radu. Hvala profesorici Suzani Ilić na potpori, čija pomoć i savjeti prije i za vrijeme boravka u Lancasteru su bili od velikog značaja.

ABSTRACT

Erosion is a physical process, characterised by significant variations in its intensity and frequency all over the world. Erosion varies upon many elements, among which the most significant are climate parameters precipitation and temperature, as well as other parameters such as geology, topography, vegetation cover and anthropogenic influences.

The topic of the dissertation is the analysis of erosion intensity and sediment production using Erosion Potential Method also known as Gavrilović method and its application in the Dubračina catchment in Vinodol Valley. This method is intended for the quantification of erosion processes by estimation of erosion intensity, sediment production and transportation of erosion sediment by river network. This method is intended for the estimation of mentioned outputs on annual basis and in the dissertation the emphasis is given upon its adjustment on the seasonal base by changing three main model parameters: precipitation, soil protection coefficient and temperature. Modified model has given good approximations of soil erosion and can be used in future research. Based on seasonal erosion sediment production estimations measures for erosion prevention and protection were proposed, as a key element for timely and adequate torrent catchment management. The sensitivity analysis was conducted as to define parameters the method is most sensitive, highlighting soil erodibility coefficient and soil protection coefficient as ones affecting it the most. The model uncertainty analysis was conducted with consideration to source and time-varying input data. Source-variant parameters have shown to have a greater impact upon model outcomes while time-variant parameters have significantly less impact upon model and their uncertainty is related to climate change in 30-year time period.

KEYWORDS: soil erosion, water erosion, Erosion Potential Method, Gavrilović method, erosion sediment production

SAŽETAK

Erozija je fizikalni proces koji karakteriziraju značajne varijacije u intenzitetu i učestalosti diljem svijeta. Erozija varira u ovisnosti o nizu elemenata, od kojih su najznačajniji klimatski parametri oborina i temperatura, te ostali parametri poput geologije, topografije, vegetacijskog pokrova i antropogenih utjecaja.

Tema doktorskog rada je analiza intenziteta i produkcije erozijskog nanosa Metodom Potencijala Erozije, također poznate kao Gavrilović metode, i njena primjena na slivu Dubračine u Vinodolskoj dolini. Temelji se na metodi potencijala erozije također poznatoj kao Gavrilović metoda, namijenjenoj kvantifikaciji erozijskih procesa procjenom intenziteta erozije, produkcije nanosa i transporta nanosa riječnom mrežom. Metoda je namijenjena za proračun spomenutih parametara na godišnjoj razini, a u radu je dan naglasak na njenu prilagodbu na sezonsku razinu promjenom njena tri glavna parametra: oborine, koeficijenta zaštite tla i temperature. Modificirani model je dao dobru aproksimaciju erozije tla i može se primijeniti u budućim istraživanjima. Na temelju procjene sezonskih produkcija erozijskog nanosa mjere prevencije i zaštite od erozije su predložene, a čine ključan segment za pravovremeno i adekvatno gospodarenje bujičnim slivovima. Provedena je analiza osjetljivosti kako bi se definirali parametri na koje je metoda najosjetljivija, pri čemu su se istaknuli koeficijent erodibilnosti tla i koeficijent zaštite tla kao najutjecajniji. Analiza nesigurnosti modela je provedena s obzirom na izvor i promjenu u vremenu ulaznog podatka. Parametri koji variraju s obzirom na izvor informacije imaju veći utjecaj na rezultate modela, dok parametri koji su promjenjivi u vremenu imaju značajno manji utjecaj na model i njihova nesigurnost proizlazi iz klimatskih promjena u 30 godišnjem vremenskom periodu.

KLJUČNE RIJEČI: erozija tla, erozija vodom, Metoda Potencijala Erozije, model Gavrilovića, produkcija erozijskog nanosa

PROŠIRENI SAŽETAK

Erozija tla je jedan od glavnih procesa koji uzrokuju degradaciju tla u svijetu. Erozija tla je dvofazni proces koji obuhvaća proces odvajanja individualnih čestica tla te njihovog transporta erozivnim agentima poput vode i/ili vjetra. Kada energija potrebna za transport čestica erozijskog nanosa više nije dostatna, dolazi do treće faze – tzv. taloženja nanosa. Posljedica erozije je razlaganje strukture tla i njegovo odvajanje na primarne čestice gline, praha i pijeska.

Tema doktorskog rada je analiza intenziteta i produkcije erozijskog nanosa Metodom Potencijala Erozije, također poznate kao Gavrilović metode, i njena primjena na slivu Dubračine u Vinodolskoj dolini. Metoda je namijenjena kvantifikaciji erozijskih procesa procjenom intenziteta erozije, produkcije nanosa i transporta nanosa riječnom mrežom.

Ulazni parametri modela podijeljeni na prostorno varijabilne i prostorno ne-varijabilne parametre. Jedan od najznačajnijih parametara je koeficijent erodibilnosti tla za čiju se procjenu predlaže primjena nomograma za evaluaciju erodibilnosti tla prema USLE (Universal Soil Loss Equation) metodi. Drugi parametar, gustoća otjecanja je analiziran i generiran primjenom tri različita pristupa koji dozvoljavaju različitu prostornu varijabilnost parametra. Do danas, ovaj parametar se je prema Gavrilović metodi izračunavao i primjenjivao kao jedna vrijednost za cijeli sliv ili jedna vrijednost za svaki podsliv, čime se ograničavala njena prostorna varijabilnost i povećavala greška izlaznih rezultata modela. Metodologija za procjenu ovog parametra primijenjena u ovom doktorskom radu daje znatno detaljniju prostornu varijabilnost i povećava preciznost i točnost rezultata modela.

Jedan od glavnih ciljeva ovog rada je provesti analizu osjetljivosti Gavrilović metode kroz analizu utjecaja četrnaest (14) različitih parametara metode na njene izlazne rezultate. Analiza je pokazala da su parametri na koje je metoda najosjetljivija prvenstveno koeficijent erodibilnosti tla te koeficijent zaštite tla. Analiza nesigurnosti modela provedena je kao nastavak na analizu osjetljivosti metode te uzima u obzir nesigurnosti izlaznih rezultata modela s obzirom na promjenu izvora informacije te promjenu vrijednosti parametara u vremenu za dva vremenska perioda (prošlost 1961-1990 i sadašnjost 1991-2020). Analizom je zaključeno da su parametri čije vrijednosti i prostorna distribucija variraju s obzirom na izvor informacije imaju značajan utjecaj na rezultate modela, gdje su posebno izdvojeni koeficijent zaštite tla te koeficijent erodibilnosti tla. Parametri varijabilni u vremenu imaju znatno manji utjecaj na rezultate modela te ukazuju na klimatske promjene u 30 (trideset) godišnjem vremenskom razdoblju. Promjene u rezultatu modela nastale kao posljedica primjene različitih izvora informacije vezani su uz ljudsku pogrešku i ovise o detaljnom preliminarnom istraživanju i prikupljanju podataka kao i o primijenjenim kriterijima za selekciju informacija. Upravo ti kriteriji su dodatno razmatrani i primijenjeni u ovom doktorskom radu.

Problemi vezani uz eroziju tla djelovanjem vode na području sliva Dubračine, Vinodolska dolina, spominju se od 19. stoljeća. U nekoliko navrata su provedene anti-erozijske mjere usmjerene ka ublažavanju i prevenciji erozijskih procesa na tom području, međutim spomenutim mjerama nije postignut zadovoljavajući rezultat. Do danas za ovo područje ne postoje karte procjene intenziteta i produkcije erozijskog nanosa, stoga je cilj ovog rada bio generirati karte i vrijednosti intenziteta erozije, produkcije erozijskog nanosa i transporta vučenog i suspendiranog erozijskog nanosa riječnom mrežom za područje sliva Dubračine na godišnjoj razini za prošlost (1961-1990) i sadašnjost (1991-2020).

Gavrilović metoda je namijenjena za procjenu erozije na godišnjoj razini, a u radu je dan naglasak na njenu prilagodbu na sezonsku razinu promjenom njena tri glavna parametra: oborine, koeficijenta zaštite tla i temperature. Modificirani model je dao dobru aproksimaciju erozije tla u usporedbi s procijenjenim vrijednostima na godišnjoj razini te je zaključeno da je primjenjiv u budućim istraživanjima. Najveći doprinos gubitku tla unutar godine dana ima jesen, zatim slijedi ljeto, proljeće i na kraju zima.

Rezultati i parametri modela verificirani su primjenom metode vizualne opservacije i GPS uređaja te je uočena iznimno visoka podudarnost s uvjetima na terenu i visoka točnost generiranih karata.

Na temelju procjene sezonskih produkcija erozijskog nanosa mjere prevencije i zaštite od erozije su predložene za područje sliva Dubračine. Građevinska zemljišta izdvojena su kao bitni, a često zanemareni izvori erozijskog nanosa te je za područja neizgrađenih građevinskih zemljišta napravljena procjena produkcije erozijskog nanosa u fazi zahvata i dan prijedlog mjera ublažavanja njenog utjecaja na ostatak sliva.

KLJUČNE RIJEČI: erozija tla, erozija vodom, Metoda Potencijala Erozije, model Gavrilovića, produkcija erozijskog nanosa

TABLE OF CONTENTS

CHAPTER 1: INTRODUCTION

One of the nine leading processes causing soil degradation in the European Countries is soil erosion. Soil erosion is a process of mechanical detachment of the soil under the influence of erosive agents such as water and wind that consists of a detachment of soil particles, transportation of detached soil and its deposition. The dominant geomorphic process for much of Earth`s land surface is soil erosion by water agent. The main influence on erosion processes are considered to have climate, soil, topography, vegetation cover and anthropogenic factors. All these elements make the environment more or less resistant to climate events.

1.1 Problem and object of the research

Water erosion related problems on Dubračina catchment have been known to exist from 19th century till today. First land instability map was made in the 1970s after the severe flash flood in the 1960s causing major damage on river structures and initiating numerous landslides in the area. During the years several attempts were made in order to mitigate erosion processes in the catchment that included reforestation measures, river regulation, construction and maintenance of structures for prevention and mitigation of erosion and flash flood with no significant effect upon the intensity of erosion processes in the area. One of the main problems is the nonexistence of erosion observations in the catchment for a longer period and their comparison in time. For this reasons, the first objective of this research are observations of erosion processes in the catchment and their comparison in time.

Till today the maps showing erosion intensity and sediment production in the catchment on the annual or seasonal level, distinguishing the areas that are more or less affected and endangered by erosion processes do not exist. This maps would enable more appropriate and on time definition of erosion mitigation and protection measures which would potentially reduce structural measures, as they are the most expensive ones, to its minimum. Structural measures have been planned at various locations in the Dubračina catchment but most of them due to the high cost have not been realised. From this problem, the third and fourth objective are defined, the third that includes the derivation of erosion intensity and sediment production, and the fourth defining the appropriate mitigation and prevention measures upon them.

In order to produce such maps a detailed and comprehensive data collection for the Dubračina catchment needed to be conducted using a variety of academic, governmental and non-governmental institutions. Since there is no unified database from which those data could be obtained the main problem in a form of multiple information sources for the same model input data has occurred. One of the main objectives and also the fifth, is to define the most appropriate information source to be used for one input data and define model uncertainty that arises from such problem.

For the chosen Erosion Potential (Gavrilović) Method, the detailed review has not been published before according to the authors' knowledge, which would enable a researcher to analyse all its potential and future modifications and implementations. Also, the sensitivity analysis of the Gavrilović method has not been conducted and the parameters the method is most sensitive to have not been determined. This review and methods sensitivity analysis are considered needed and essential in order to achieve third to fifth objectives, which makes this the sixth and seventh objective of this research.

1.2 Research aims and hypothesis

Based on defined research problems and objectives, research aims are defined. Following ***Research aims*** include:

1. Analysis of the possibility to modify the chosen method from annual time intervals to seasonal time intervals
2. Analysis of erosion processes on the Dubračina catchment that includes the assessment of total annual and seasonal volume of the detached soil
3. Analysis of erosion processes that include the derivation of maps representing erosion intensity, total annual volume of the detached soil, and actual sediment yield for the past (1961 – 1990) and present (1991 – 2020) time on annual basis, as well as for the present time (1991 - 2020) on seasonal basis for the Dubračina catchment
4. Mitigation and protection erosion measures proposed for the area of Dubračina catchment

5. Method adjustment to local conditions in the catchment by improving the soil erodibility coefficient and soil protection coefficient by the integration of more appropriate gradation elements
6. Sensitivity method analysis to all parameters and determination of the most sensitive parameters influencing the method
7. Model uncertainty analysis due to information source change for land cover/use and soil erodibility coefficient for the present time 1991 - 2020
8. Model uncertainty analysis due to time-variant parameters: precipitation, temperature and land cover with consideration to past (1961-1990) and present (1991-2020) time
9. Verification of the model

Based on defined research aims the following hypothesis is defined:

Hypothesis: Gavrilović method can be modified for the purposes of total seasonal sediment production assessment and the knowledge about the changes in the precipitation parameter as a key climate change parameter is in long-term and on a seasonal level for the analysed catchment essential as to acknowledge the cycle of sediment production change with an aim to improve torrent catchment management. Gavrilović model is sensitive to, and uncertain due to information source change of, a parameter defined by land cover/use.

Research support:
All research presented in this thesis is conducted within the three scientific research projects:

1. „*Risk Identification and Land – Use Planning for Disaster Mitigation of Landslides and Floods in Croatia*“, project leader: prof.dr.sc. Nevenka Ožanić
2. “*Development of New Methodologies in Water and Soil Management in Karstic, Sensitive and Protected Areas*”, project No.: 13.05.1.3.08, project leader: izv.prof.dr.sc. Barbara Karleuša
3. *“Hydrology of Sensitive Water Resources in Karst”*, project No.: 114-0982709-2549, project leader: prof.dr.sc. Nevenka Ožanić

Software used in research:
The research presented in this thesis was conducted using following software: ArcGis 10.2, ERDAS Imagine 14. The satellite images were extracted with the help of Glovis USGS Viewer

and processed in the ERDAS Imagine 14 software. The Gavrilović model was made and processed in the ArcGIS 10.2. Some analysis included the Microsoft Excel software, as well as Geospatial Modelling Environment software complemented with R i386 3.2.3 statistical software. For visual survey monitoring GPS and camera were used.

1.3 The structure of the doctoral thesis

Besides the ***Abstract*** in English and Croatian language and ***Table of Contents***, the doctoral thesis comprises of twelve (12) interconnected chapters that encompass conducted research and its results.

Chapter 1: Introduction

In this chapter, the research problem, objectives, aims and hypothesis are defined and form the basis of this thesis. Also, the structure of the thesis is defined and shortly elaborated.

Chapter 2: Soil erosion and related basic definitions

Definitions of terms, classification of soil erosion and explanation of erosion processes essential for this research are explained in this chapter. Factors influencing soil erosion are named and some known facts connecting erosion processes within each factor group are given. One section of this chapter refers to the role of civil engineering in soil erosion management with reflection on Croatian laws and regulations related to erosion prevention and mitigation measures.

Chapter 3: Dubračina catchment characteristics and historical overview of the problems and measures related to land instability

Catchment characteristics, historical overviews of the erosion problems, conducted anti-erosion measures to this day have been described in this chapter. Also, all previously conducted research on the erosion processes in the catchment has been gathered and presented including the research about involvement and risk awareness of the local population about flash floods and erosion in Dubračina catchment.

Chapter 4: Choosing the model for soil erosion sediment production assessment

Within this chapter, model classifications have been mentioned and future research narrowed to semi-quantitative methods. A short review of previous research related to erosion assessment method selection has been given along with the list of considered models and the analysis of parameters significance according to their use in the listed methods. The main section of this chapter refers to the proposition and use of the methodology for the erosion assessment method selection.

Chapter 5: A review of the Erosion Potential (Gavrilović) Method application

A detailed overview of the Erosion Potential (Gavrilović) Method (EPM) implementation for erosion intensity and sediment assessment, as well as conclusions and suggestions for future development and improvement of the method and its application are given in Chapter 5.

Chapter 6: Method parameter description and data availability

The description of each parameter used in the model is given, including its information source, derivation process and their characteristics. The necessary data (parameters) are subdivided into spatially variant input parameters (precipitation, temperature and land cover/use, soil erodibility, average slope of the study area) and spatially invariant parameters (study area, perimeter of the watershed, length of the principal waterways and calculated length of the principal and the secondary waterways).

Chapter 7: Deriving drainage density parameter

An entire chapter is devoted to drainage density parameter that represents the amount or rivers in the catchment needed to drain the basin. The factors affecting drainage density, related research and different drainage density map derivation methods are listed. Within, the drainage density relation to soil erosion is also highlighted. The methodology used for the derivation of the drainage density map for Dubračina catchment is explained in detail.

Chapter 8: Source and time-varying input data in context of Erosion Potential Method based model uncertainty

Within this chapter, the model uncertainty analysis due to source and time-varying input data is given based on sample size. The reflection on model time-variant and source-variant uncertainty were given separately with join conclusions at the end of the chapter. One of the sections in this chapter includes method sensitivity analysis to fourteen different parameters and conclusions deriving from it.

Chapter 9: Annual and seasonal erosion sediment production on the Dubračina Catchment

Two main subsections form Chapter 9. The first encompasses the Gavrilović model results and maps related to the estimation of the annual values for the erosion sediment production and erosion intensity for two-time series, the past and the present. In the second section, parameters modified and changed in order to produce seasonal output values and maps from a model are presented. The annual and seasonal results, as well as the application of proposed modifications, are discussed.

Chapter 10: Erosion model verification

In this chapter applied erosion monitoring methods on the Dubračina catchment and its results are presented. When selecting the measurement method several different factors were taken into consideration and named in this chapter. The verification method of Landsat derived land cover map for present and summer time, the verification of erosion coefficient (intensity) map and changes in soil surface are presented and elaborated.

Chapter 11: Erosion mitigation measures recommendation for future soil and water management in Dubračina catchment

Erosion mitigation and prevention measures for the Dubračina catchment are proposed with considerations to the economic cost of these measures. The influence of construction sites on erosion sediment production is assessed followed by proposed measures for its prevention and mitigation.

Chapter 12: Conclusion

General conclusion deriving from research results presented in this thesis are given, as well as a recommendation for future research and guidelines for local government related to erosion mitigation and prevention.

CHAPTER 2: SOIL EROSION AND RELATED BASIC DEFINITIONS

The soil is an un-renewable valuable natural resource and a dynamic system essential for human sustainability (de Vente, 2009; 2004/35/EC). According to the Proposal for Directive for the Protection of Soil and the Amending Directive from 2004 (2004/35/EC), there has been a significant increase in soil degradation processes in the last decades. If not managed properly and on time, this trend will continue in the future, possibly leading to the abandonment of activities on soils affected by intensive degradation processes and eventually depopulation of areas dependent on it.

There are eight leading processes causing soil degradation in the European Countries, among which erosion is considered the main and the most wide spread (2004/35/EC). According to Gavrilović (Gavrilović, 1972) soil erosion poses the biggest threat to soil and water conservation in semi-arid areas.

The processes of sediment generation, transport and deposition have been well described in more detail elsewhere (e.g. Morgan, 2005; Šurda et al., 2007; Toy, et al., 2002) and are discussed in this chapter only to introduce the concepts of these processes.

2.1 Soil erosion classification and basic terms definition

The term ***erosion*** (*lat. erodere – to eat away, to excavate*) was first used in geology to describe the forming of hollows by water and the wearing away of solid material by the action of river water. Meanwhile, a surface wash and precipitation erosion were called ***ablation*** (*lat. ablatio – to carry away*). Although the term erosion was in use in the 19th century, the term soil erosion was introduced later, at the beginning of the 20th century (Zachar, 1982).

Šurda et al. (2007) defines ***soil erosion*** *as a processes of mechanical detachment of the soil under the influence of erosive agents such as water and wind that consists of three phases: (i) detachment of soil particles, (ii) transportation of detached soil and (iii) its deposition*.

There are many classifications of soil erosion, some of which are shown in Table 1. Furthermore the classification of soil erosion caused by water agent (“water erosion”), which is later referred in this thesis, is also provided.

Table 1: Classification of soil erosion depending upon erosive agents and local conditions by different authors

Soil erosion			**Water erosion**		
By the intensity (Blanco and Lal, 2008; Morgan, 2005)	***By the erosive agent***		(Blanco and Lal, 2008)	(Toy et al., 2002)	***Croatian local conditions*** (Kisić et al, 2005):
	(Šurda et al., 2007)	(Zachar, 1982)			
Natural or Geologic Accelerated	Water Cryogenic Wind Organic Anthropogenic Snow	Water, aquatic or hydric Glacial Snow or nival Wind or Aeolian Ground or soilgenic Zoogenic Phytogenic Anthropogenic	Splash Interill Rill Gully Streambank Tunnel	Sheet Interill Rill Gully Stream-Channel	Splash Sheet Rill Gully Stream-Channel Deep karst erosion Landslides

Dominant geomorphic process for much of Earth`s land surface is soil erosion by water (Toy et al., 2002). Water erosion is considered the most severe type of soil erosion where soil detachment and transportation is caused by two different phenomena, the first being the raindrop impact on soil and the second water runoff (Blanco and Lal, 2008). According to Toy, et al. (2002) ***water erosion*** is "*a function of forces applied to the soil by raindrop impact and surface runoff relative to the resistance of the soil to detachment*". A detachment of sediment from the soil surface was originally considered to be exclusively the result of raindrop impact, although the importance of overland flow as an erosive agent has later been recognised (Merritt et al., 2003). Today, rainwater in the form of runoff is considered the main trigger of water erosion causing the transport of soil particles and its deposition on lower parts of the catchment. Definitions of basic terms related to water erosion are given below:

*"**Sediment delivery** is the amount of eroded material delivered to a particular location, such as from the eroding portions of a hillslope (soil loss) or the outlet of a catchment (sediment yield)"* (Toy et al., 2002).

Soil loss *refers to the sediment from the eroding portion of a hillslope where overland flow occurs* (Toy et al., 2002).

*"**Sediment discharge** from a catchment is the total quantity of sediment moving out of the catchment in a given time interval (mass/time). The total sediment discharge from a catchment relative to the catchment area is also called **sediment yield** (mass/area/time)"* (Lane et al., 1997).

"***Sediment yield*** *and* ***sediment delivery*** *express the rate or amount of sediment transported to a point of measurement, at the base of a hillslope, the boundary of a field, in a stream channel, or at the mouth of a catchment"* (Toy et al., 2002). Sediment yield directly reflects the characteristics of a catchment, its history, development, use and management (Lane et al., 1997).

A ***catchment*** *(also referred in the literature as* ***watershed*** *and* ***river basin****) according to Lane, et al. (1997) is defined by its perimeter and can be described with a respect to surface runoff where the catchment perimeter presents a boundary where runoff produced inside the perimeter will move to the catchment outlet*.

Water erosion can occur in all types of soil at different rates and in different forms (see Table 1). All these erosion types do not necessarily occur in isolation from one another and are influenced by various factors affecting erosion (such as climate and topography) (Merritt et al., 2003). One of the most spectacular forms of water erosion with the capacity to cause severe soil erosion in only one high intensity rainfall is gully erosion (Toy, 2002). Within this thesis, the emphasis will be given on the erosion sediment assessment for areas affected by gully erosion formations.

2.2 Gully erosion

Gullies are permanent steep water paths, characterised by a headcut and various steps or knick-points along their course, activated during rain events (Morgan, 2005). In comparison to river channels gullies are relatively deeper and smaller in width, can transport larger amounts of sediment loads and are often unpredictable in a sense of small relationship between sediment discharge and runoff. It should be noted that gullies are "almost always associated with accelerated erosion" (Morgan, 2005). Gully erosion often creates V or U-shaped channels and the process of single gully formation on hillslope is shown in Figure 1.

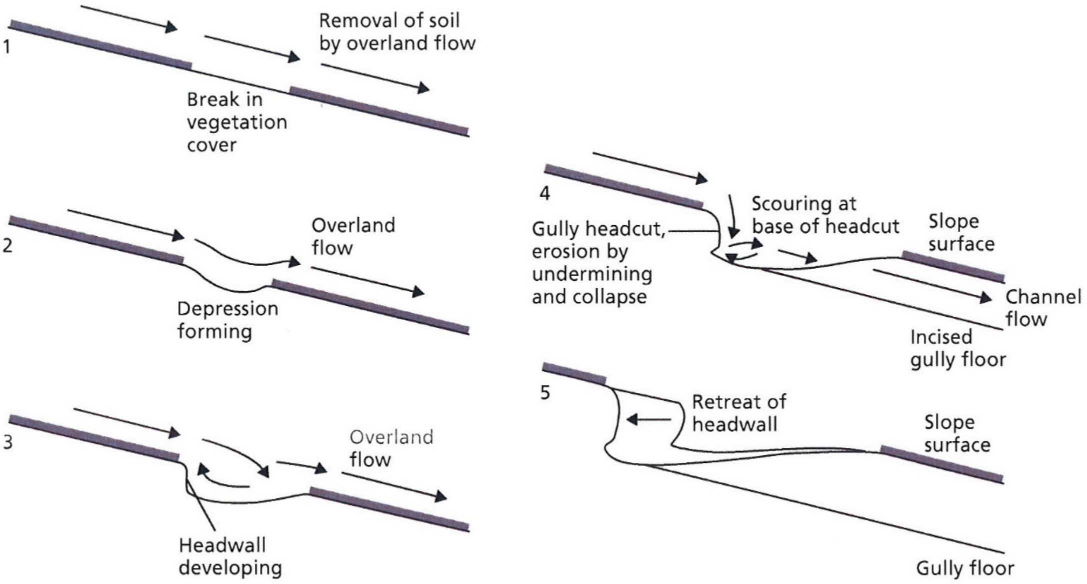


Figure 1: Hillside gully development in stages (Morgan, 2005)

According to Morgan (2005) large amounts of water are the main cause in the formation process of gullies. Also, erosion rate on each individual gully is considerably high in comparison to the erosion rate on the entire research catchment. The reason for that is that in most cases the overall catchment area coverage with gullies do not exceed more than 15 percent (%). According to Poesen et al. (2003) from 10 up to 94% of total sediment yield caused by water erosion are related to gully erosion soil loss.

The definition of gully erosion states that the occurrence of runoff water often in a narrow channels over a short period of time causes the removal of soil particles up to considerable depths (Poesen et al., 2003). In comprehensive review research related to gully erosion case studies Poesen et al. (2003) has indicated that gully erosion greatly influence soil degradation processes consequently causing considerable soil losses with a large volume of detached sediment. Within this processes gullies also act as intermediaries transporting water runoff and sediment particles to valley bottoms and river beds. Subsequently, sediment transportation caused by erosion processes downstream can affect river capacity and drainage paths and consequently increase the risk from flooding of surrounding area (Morgan, 2005).

2.3 Factors influencing soil erosion

The most important elements by world scientific literature (e.g. Morgan, 2005) that influence the rate of erosion are climate, soil, topography, vegetation cover and anthropogenic factors. All these elements make the environment more or less resistant to climate events. Comprehensive list of the factors affecting water erosion, and grouped according to the main elements affecting the erosion, were given by Blanco and Lal (2008) (Table 2 and 3).

Table 2: Main factors affecting soil erosion and some known facts connecting erosion processes and each factor group (Blanco and Lal, 2008)

Climate	**Vegetation cover**	**Topography**	**Soil properties**
All climatic factors (e.g. precipitation, humidity, temperature, evapotranspiration) affect water erosion.	Vegetative cover reduces erosion by intercepting, absorbing and reducing the erosive energy of raindrops.	Soil erosion increases with increase in field slope.	Texture organic matter content, macroporosity and water infiltration influence soil erosion.
Precipitation is the main agent of water erosion.	Plant morphology such as height of plant and canopy structure influences the effectiveness of vegetation cover.	Soil topography determines the velocity at which water runs off the field.	Antecedent water content is also an important factor as it defines the soil pore space available for rainwater absorption.
Amount, intensity and frequency of precipitation determine the magnitude of erosion.	Surface residue cover sponges up the failing raindrops and reduces the bouncing of drops. It increases soil roughness, slows runoff velocity, and filters soil particles in runoff.	The runoff transport capacity increase in slope steepness.	Soil aggregation affects the rate of detachment and transportability.
Intensity of rain is the most critical factor.	Soil detachment increases with decrease in vegetative cover.	Soils on convex fields are more readily eroded than in concave areas due to interaction with surface creeping of soil by gravity.	Clay particles are transported more easily than sand particles, but clay particles form stronger and more stable aggregates.

The more intense the rainstorm, the greater the runoff and soil loss.	Dense and short growing (e.g. grass) vegetation is more effective in reducing erosion than sparse and tall vegetation.	Degree, length, and size of slope determine the rate of surface runoff.	Organic materials stabilise soil structure and coagulate soil colloids.
High temperature may reduce water erosion by increasing evapotranspiration and reducing the soil water content.	The denser the canopy and thicker the litter cover, the greater is the splash erosion control, and the lower is the total soil erosion.	Rill, gully and stream channel erosion are typical of sloping watersheds.	Compaction reduces soil macroporosity and water infiltration and increases runoff rates.
High air humidity is associated with higher soil water content.		Steeper terrain slopes are prone to mudflow erosion and landslides.	Large and unstable aggregates are more detachable.
Higher winds increase soil water depletion and reduce water erosion.			Interactive processes among soil properties define soil erodibility.

Table 3: Anthropogenic factors related to land use activities and social and economic conditions (Morgan, 2005)

Land use	**Social and economic conditions**
Deforestation	Forest fires
Overgrazing	Ineffective conservation policies
Urbanization	Poorly defined land tenure
Slashing and burning	Lack of incentives and weak institutional support
Mining	High population density
Industrial activities	Low income
Road constructions	

According to Morgan (Morgan, 2005) the occurrence of erosion processes, its distribution and timing depends on many physical and chemical factors but is also closely related to anthropogenic factors such as social, economic and political local conditions (Table 3). Such erosion often relates as “accelerated” erosion caused by human activities upon the environment and leads to transformation of this areas into unproductive soils and eventually to its abandonment. Also, activities such as deforestation, intensive cultivation, soil mismanagement and urbanisation, all of which fall in the domain of land use management, influence soil erosion rates and intensify soil erosion hazards (Blanco and Lal, 2008).

Public interest on erosion in a certain area depends greatly on the intensity, spatial distribution and directly visible and perceptible erosion processes in a relatively short period of time. Unfortunately, erosion is a slow process and as such often difficulty noticeable to the human eye in a short period of time while its long-term observation in the area is neglected (Zorn and Komac, 2011). According to the research by Renschler and Harbor, (2002) only a small frequency events of great magnitude arouse public interest for impact assessment, prevention and management of such phenomena. In contrast, events and processes with small frequency and large magnitude, such as erosion, remain unnoticeable and in long-term without any significant public interest.

2.4 The role of civil engineering in soil erosion management

The torrents are permanent or occasional streams whose characteristics are: highly variable discharges, high slope gradients of the bottom, high scouring activity, transport and deposition of sediment and frequent changes of channel dimensions. They are often followed by erosion processes and as its result, downstream erosion sediment transport (Croatian Water act, 2009; Novák, 1994).

The main triggers of severe erosion and torrential floods are overexploitation of forest and agricultural land followed by the area urbanisation. The ultimate consequence of such areas where soil erosion has almost irreversibly changed the environment are changes in land use leading to the abandonment of agricultural land. Today, soil erosion is considered a multidisciplinary problem, being considered within civil engineering, agro-engineering, bio-engineering, hydrology, geology, geomorphology to even economy (Ristić et al., 2011b).

Erosion processes result in direct (onsite) effects such as soil loss, water loss, gully development, decreasing soil fertility and disturbance of the water regime, and indirect effects, that are less noticeable but not irrelevant such as environmental pollution, enhanced flood risk due to river sedimentation and reduced water reservoir capacity and damage to buildings and infrastructure, especially reservoirs. Since off-site erosion effects are much less visible they are also less studied (Blinkov et al., 2010).

In the 19th Century, the erosion and torrent control works implementation have started in Europe (Ristić et al., 2011b). Today, successful erosion management depends on a proper selection and combination of appropriate structural and non-structural measures, based on the characteristics of the research area, its physical and morphological characteristics, economic, social, political and environmental conditions (Morgan, 2005). According to the World Meteorological Organization (WMO) erosion management needs to be based on structural and non-structural protection and mitigation measures. Structural measures are considered traditional engineering measures used in prevention against flash flood and erosion (Novák, 1994; McMinn, et al., 2010). Traditional approaches most commonly use engineering solutions such as revetments and retaining walls used for the stabilisation of the slope, contour bunds, terraces, silt fences, etc. (Morgan, 2005; Novák, 1994; McMinn, et al., 2010).

Erosion control strategy is oriented towards mitigation of on-site erosion effects related to water erosion within the water management sector, such as annual intensity of sediment load into the river network, the intensity of siltation of the reservoirs, the quantity of sediments deposed downstream etc. (Blinkov and Kostadinov, 2010). There are various soil conservation techniques that can be assigned to a group of agronomic, soil management or mechanical methods. Agronomic measures emphasise the importance of vegetation cover in the intensity of erosion processes and influence both the detachment and transport erosion. Mechanical or physical methods are more related to engineering structures aimed to control the flow of water and have an effect mainly on sediment transport (Morgan, 2005).

Croatian laws and regulations as a prevention and mitigation measures for flash flood control specify actions that fall into the category of structural measures with characteristics of erosion protection and river bed stabilisation. Such works are protection barriers, river regulation construction and maintenance of structure with water protection purpose, reforestation of catchment areas, cultivation and maintenance of protective vegetation as well as removal of vegetation on required areas, removal of sediment from waterbed, construction and maintenance of structures for prevention and mitigation of erosion and flash flood, prohibition and limitation for excavation of sand, gravel and stone, etc. (Croatian Water Act, 2009; Water Management Strategy, 2009; Glavni provedbeni plan obrane od poplava, 2011). According to Croatian Water Act (2009) anti-erosion measures include various legislation measures, education of population regarding problems of erosion and flash floods, systematic monitoring of erosion processes, the formation of databases about erosion affected land and applied anti-erosion measures, integrating erosion protection measures in spatial planning, and so on.

During the years the most attention in soil erosion research was given upon agricultural land. Today, it is well known that erosion processes are not restricted only to an agricultural area and in a non-agricultural areas destruction of roads, trackways and footpaths, sedimentation of river beds or exposure of pipelines are just some erosion effects needing attention. Every day, more and more organisations like highway agencies, engineering companies and pipeline companies take actions toward erosion mitigation in order to retain their management reputation (Morgan, 2005).

Construction sites, in the areas of urban expansion and erosion prone areas, if not managed properly result in higher volumes of peak runoff, shorter times to peak flow, higher and more frequent flood flows and rapid increases in erosion by overland flow, rills and gullies, all of which contribute to the higher detachment values of erosion sediment. Erosion management in urban areas requires in advance erosion protection measures planning in a form of revegetation of the construction site upon the completion of engineering works, retaining the erosion sediment using e.g. silt fences or burlap rolls and/or many more different and available measures (Morgan, 2005).

Restoration of pipelines is in most cases directed toward the restoration of the original vegetation cover in the shortest period of time. Inappropriate construction practice can be a major initiator of erosion processes in a pipeline corridor (Morgan, 2005).

Road banks are another frequent source of sediment associated with runoff and sediment transport. A land between the road surface and the side drain is vulnerable to erosion (Morgan, 2005).

One interesting research regarding the applicability of different erosion models (Corine, the Hot Spots, Universal Soil Loss Equation (USLE), Pan-European Soil Erosion Risk Assessment (PESERA), The European Soil Erosion Model (EUROSEM), The Water Erosion Prediction Project Model (WEPP), Kinematic Runoff and Erosion Model (KINEROS) and Erosion Potential (Gavrilović) Method) for various engineering purposes integrated within erosion mitigation strategy and control measures was given by Blinkov et al. (2010). Their analysis has shown that applicability of these methods for engineering purposes vary from sector to sector, where the sectors encompassed with this analyses are agro-engineering, bio-engineering and watershed management. They concluded that not all methods (such as Corine, GLASOD, INRA) are applicable for solving an engineering problem and can provide only a general information of the state of erosion processes and result in general planning.

CHAPTER 3: DUBRAČINA CATCHMENT CHARACTERISTICS AND HISTORICAL OVERVIEW OF THE PROBLEMS AND PREVENTION AND MITIGATION MEASURES RELATED TO LAND INSTABILITY

3.1 Case study: Dubračina catchment characteristics

The method and model analysis described in this thesis are based upon research and gathered data from Dubračina Catchment area (Figure 2), situated in the Vinodol Valley in the County of Primorsko-Goranska, Croatia.

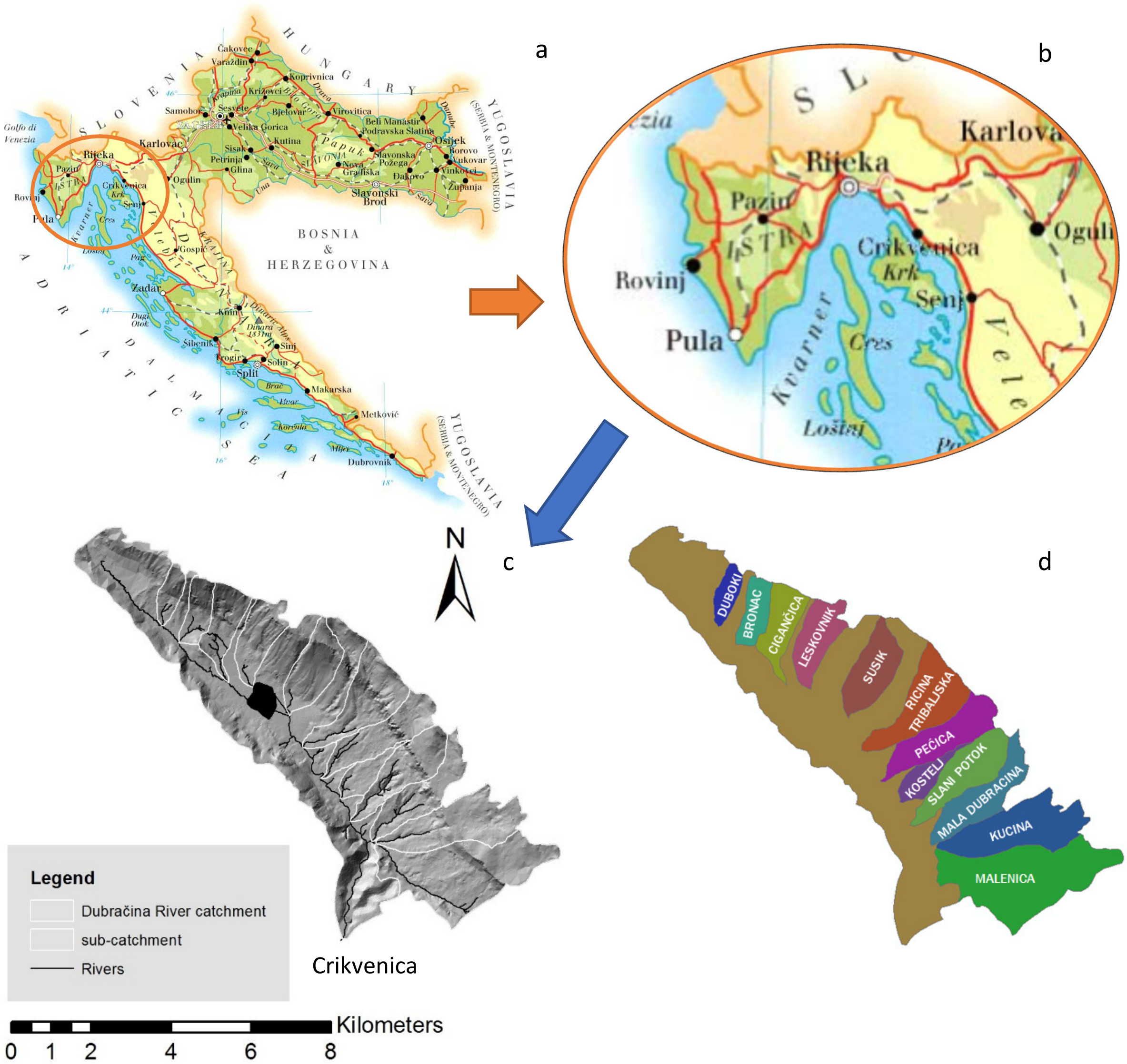


Figure 2: Dubračina catchment: (a-c) location, (c) variations in elevation and drainage patterns and (d) Sub-catchment distribution

This small catchment, 43 km^2 in size, is characterised by its valuable natural and cultivated landscape, biodiversity, cultural, historical heritage and also high annual rainfall, steep topography and variable geology all of which contribute to its land instability such as landslides and excessive erosion processes. Besides of the obvious lack of land stability all the above-mentioned characteristics also provided the area the status of a "Protected Area of Great Importance".

Dubračina River and its twelve tributaries (see sub-catchment distribution in Figure 2d and its characteristics in Table 4), all with torrential characteristics, count approximately 41 km in length. Although most of its tributaries tend to dry out during the summer period, during the rainy period considerable flow oscillations are very common.

Table 4: Basic cub-catchment characteristics and ratio in Dubračina catchment

TRIBUTARY	**AREA**		**RIVER NETWORK LENGTH**	
	[km^2]	**[% DUBRACINA CATCHMENT]**	**[km]**	**[% OVERALL PRIMARY AND SECONDARY RIVER LENGTH]**
DUBOKI	0.67	1.53%	0.96	2.34%
BRONAC	0.99	2.27%	1.62	3.95%
CIGANČICA	1.49	3.43%	3.03	7.39%
LESKOVNIK	1.62	3.73%	0.87	2.12%
SUSIK	1.93	4.42%	0.78	1.90%
RICINA TRIBALJSKA	2.74	6.29%	1.71	4.17%
PEĆICA	2.23	5.13%	2.32	5.66%
KUČINA	0.82	1.88%	1.04	2.54%
SLANI POTOK	2.21	5.07%	3.22	7.86%
MALA DUBRACINA	2.09	4.79%	3.00	7.32%
KUCINA	3.29	7.55%	1.52	3.71%
MALENICA	5.54	12.72%	4.00	9.76%
DUBRACINA RIVER	17.94	41.19%	13.69	33.40%
SMALL UNNAMED TRIBUTARIES			3.23	7.88%
SUMMARIZED	**43,56**	**100,00%**	**40,99**	**100,00%**

The overall catchment can roughly be divided into the upper karstic part with steep slopes and active sediment movement and lower Flysch as less permeable area. Complex geological structure, special valley cross section with distinct steep slopes affected by erosion, local landslides and torrents are the reason this area has been known for many years as an area of potential hazard risk (Figure 3). High rainfall followed by active erosion processes can potentially endanger lower parts of the catchment area especially the centre of tourist town Crikvenica where Dubračina River is joined with the sea.

Figure 3: (a) Sediment in tributary Malenica riverbed, (b) Land instability: intensive erosion processes causing local landslides on Slani Potok sub-catchment (c) Road damage due to land instability on border of Slani Potok and Mala Dubračina sub-catchments, (d) Unmaintained river bed of one of the Dubračina tributary's [photographs taken by author]

3.2 Historical overview of the problems and conducted anti-erosion measures

The first written report on erosion in the Dubračina Catchment, within the Slani Potok and Mala Dubračina sub-catchments, date from the late 19th century. After a severe flash flood at the beginning of the 1960`s, that caused major damage to river structures and initiated numerous landslides in the Slani Potok sub-catchment, the first land instability map for the most endangered sub-catchments in Dubračina catchment was made (Figure 4).

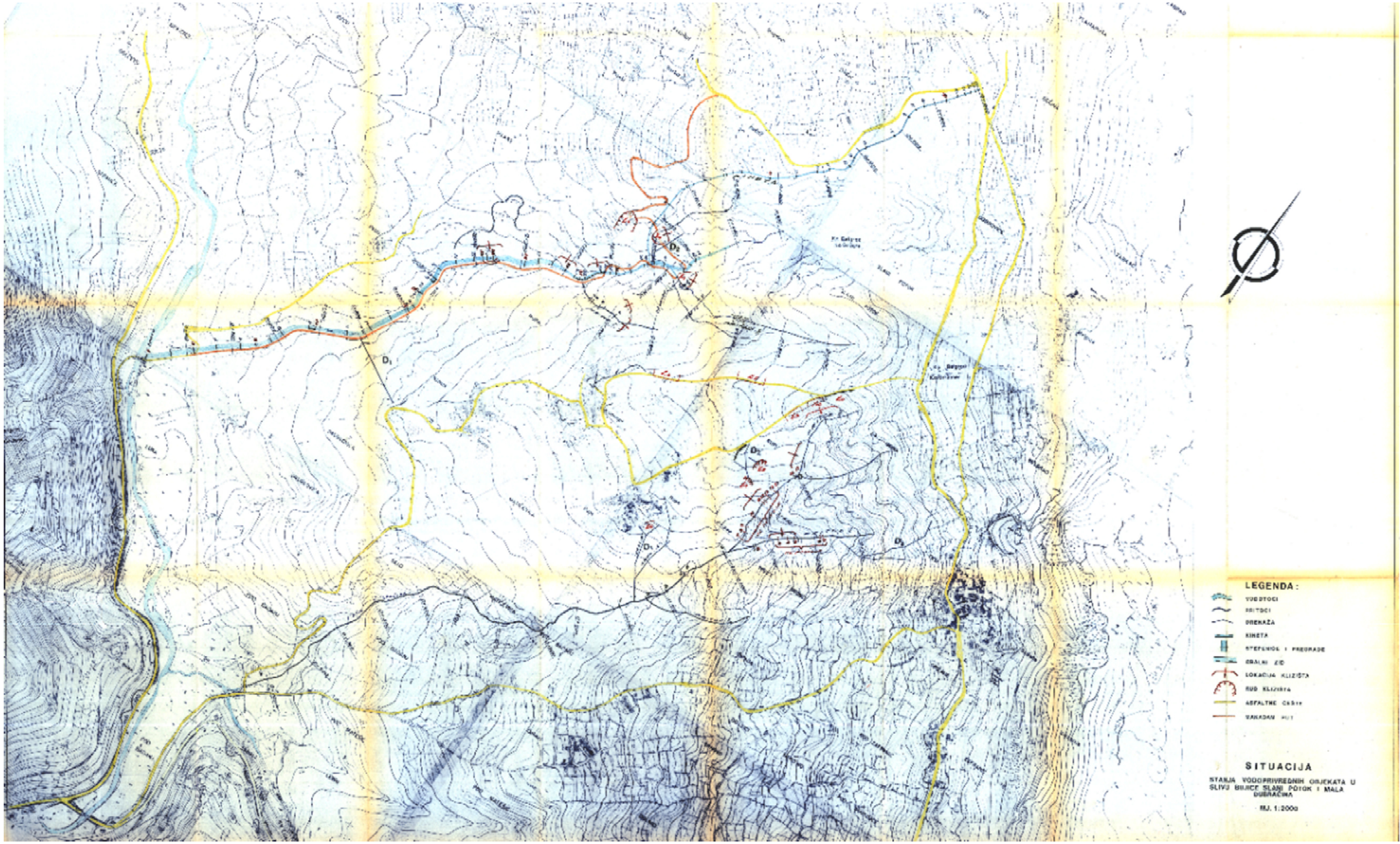


Figure 4: First map indicating land instabilities in Slani Potok and Mala Dubračina sub-catchments dating from 1970`s [source local inhabitants archive]

During the past, flash flood and erosion prevention and mitigation measures were conducted several times (Figure 5). They included river regulation, construction and maintenance of structures for prevention and mitigation of erosion and flash flood, as well as reforestation of the catchment area and reconstruction of areas affected with land instabilities. All these measures didn't have much success in preventing the expansion of erosion affected areas. These sub-catchments remain most affected by erosion processes to this day, containing the largest areas to be characterised as experiencing excessive erosion (Figure 2c). Today this area faces threat of erosion in some parts of villages as well as roads all around the Dubračina catchment area and mostly around Slani Potok and Mala Dubračina sub-catchments (Figure 3) (Bonacci et al., 2010., Dragičević et al., 2012., Ožanić et al., 2012, Dragičević et al., 2014a).

Figure 5: Local population involved in mitigation measures: reforestation of erosion affected areas (source local inhabitants archive)

During the development of Spatial Plan (2004) mapping of erosion affected areas was made indicating four sub-catchments of Dubračina catchment (Slani Potok, Mala Dubračina, Balasi and Kučina) as erosion threatened areas (Figure 6).

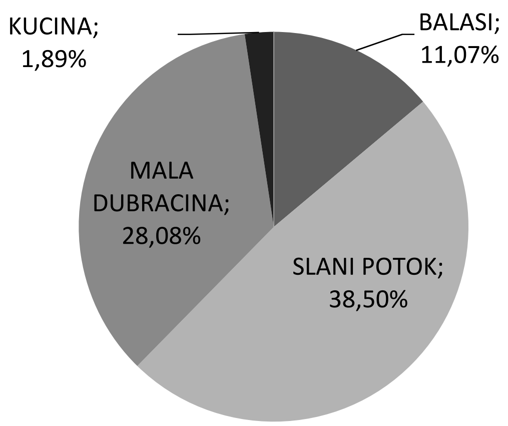


Figure 6: Sub-catchment area percentage affected by erosion processes (based on Spatial Plan, 2004 source)

During the years numerous geological, engineering-geological, hydrogeological and geomechanical projects were made containing conceptual ideas on the restoration of areas affected by land instabilities (erosion and landslide affected areas) in Dubračina catchment. In 2004, anti-erosion measures, such as:

- supporting and improving restoration measures for erosion affected areas,
- ensuring the maintenance and improvement of existing anti-erosion systems,
- prohibition of new content due to the geological sensitivity of the area,
- monitoring and research of erosion process,
- protection of cultural and historical valuable structures from erosion, torrents and floods

were proposed within the Spatial Plan of Vinodol Valley, but without any further elaboration (Spatial Plan, 2004). One of the projects suggested numerous structural measures on entire sub-catchment Slani Potok (Idejno rješenje uređenja sliva Slani Potok, 2010) and included cadastral of land instabilities in the sub-catchment along with future measures proposition and frequency for long-term monitoring of erosion processes ("erosion pins").

During the rainy season, the density of water network increases in the entire Dubračina catchment area activating all torrential tributaries and forming additional water paths with torrential characteristics. This phenomenon directly triggers erosion processes in the area. The area around Slani potok and Mala Dubračina sub-catchment are covered with flysh material that is generally considered impervious and has low infiltration coefficient. During a rainfall event, one part of the water infiltrates in the ground surface but most of it forms surface runoff due to high runoff coefficient. Intensive water erosion processes are as mentioned before especially visible in Slani Potok sub-catchment area in the form of splash and gully erosion with characteristics of excessive erosion (Figure 7).

According to Benac et al. (2005), Jurak et al. (2008) and Aljinović et al. (2010) this phenomenon can be related to the unique occurrence of Thenardite mineral in the area of Slani Potok sub-catchment. The soil research in the last decade led to a conclusion that high erodibility of the area around Slani Potok sub-catchment can be directly related to specific mineral composition of lithological flysch components in this case Thenardite mineral, visible as a white powdery substance that tastes bitter-salty and is responsible for the name origin of the Slani Potok (eng. *Salty Creek*) tributary.

During the years there were several attempts to estimate the amount of erosion sediment production in the area.

The first estimation of erosion sediment production was made using Universal Soil Loss Equation (USLE) in 1997. by Faculty of Agriculture University of Zagreb (Kisić and Bašić, 1997, Kisić et al., 2000).The approach was to divide the area into six different soils types spread across Vinodol Valley. The division was based upon Pedology map 1:50 000 dating from 1986 and additional field and laboratory research was carried. It should be noted that Vinodol Valley, included in the research, consists of two main catchments, the one smaller Suha ričina Novljanska and the bigger one Dubračina. For most soil types calculated average annual soil loss didn't exceed tolerated soil loss calculated with USLE method except for the colluvial and soil rendzina on the colluvial drift. For moderately deep soils the value for tolerated soil loss is 8 t/ha/year (approximately 500 m^3/km^2/year) and for very deep to deep soils 12 t/ha/year (approximately 750 m^3/km^2/year). According to this research (Kisić and Bašić, 1997, Kisić et al., 2000), calculated erosion risk level for Vinodol Valley ranges from slight to very high on moderately deep soils and moderate erosion risk on very deep to deep soils (Kisić and Bašić, 1997, Kisić et al., 2000).

In 2010, within the project regarding reconstruction and maintenance of Slani Potok sub-catchment (Idejno rješenje uređenja sliva Slani Potok, 2010) rough estimation of Total annual volume of detached soil and sediment transported downstream through river network was made only for two smaller areas (0.016 and 0.012 km^2) on Slani Potok sub-catchment (2.21km^2) using Gavrilović method and assuming homogenous characteristics/values for each parameter in the method. Obtained value for annual erosion sediment production were 2835 $m^3/km^2/year$ and values for sediment transporting downstream (using Original Gavrilović formula – see Chapter 5: A Review of the Erosion Potential (Gavrilović) Method application) range from 910 up to 1077 $m^3/km^2/year$.

Most of the existing projects, mentioned here, were partially or never implemented. To this day realised projects and measures included only structural measures that by their characteristics fall within short-term measures with strong impact upon nature. For the successful flood and erosion management on Dubračina River catchment area, which falls within sensitive areas and areas of special significance, it is essential and recommended that measures proposed by Spatial Plan, are also complemented by measures such as public involvement; implementation of flood and erosion risk prevention and mitigation actions before, during and after hazard within educational institutions and establishment of continuously and long-term monitoring of erosion processes. Furthermore, since precipitation and runoff have a great impact on erosion sediment production and sediment yield transport, in the long-term the establishment of an early warning system related to the amount of precipitation, water level and flow velocity should be considered (Dragičević et al., 2013a).

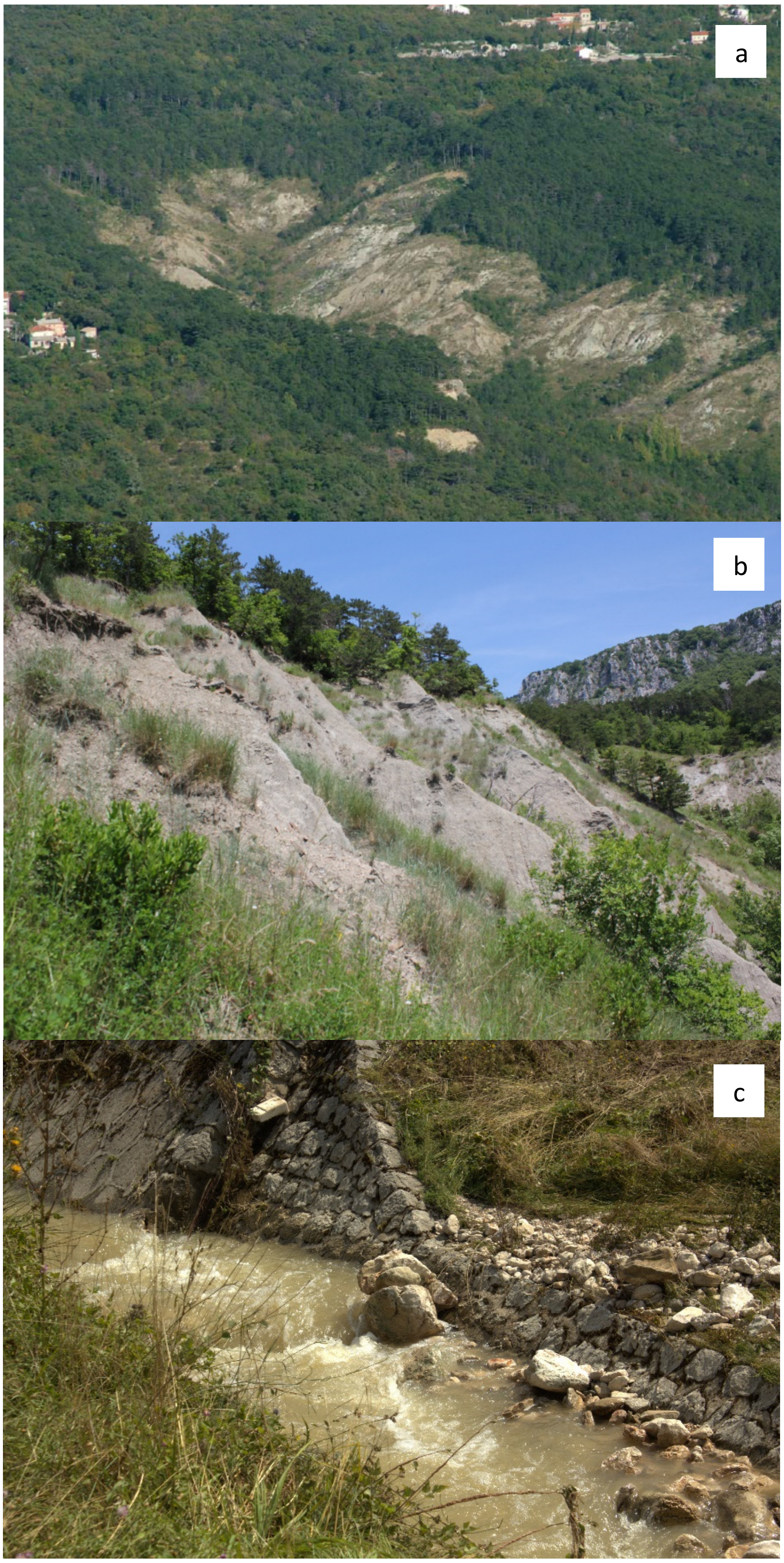


Figure 7: Visible erosion processes (a) Area affected by excessive erosion processes in Slani Potok sub-catchment (Spatial Plan, 2004), (b) Gully erosion at Slani Potok sub-catchment (photograph taken by author), (c) Sediment transport and river bed erosion (photograph taken by author)

The research about involvement and risk awareness of the local population about flash floods and erosion in Dubračina catchment was conducted by author within the international bilateral Croatian-Japanese project “***Risk Identification and Land-Use Planning for Disaster Mitigation of Landslides and Floods in Croatia***”. The main objective of the research was to define the local population risk awareness about flash floods and erosion in the area, as well as their interest to be involved in the decision making process aimed at flood and erosion mitigation and prevention strategy. The research was conducted through surveys in May 2012. (Dragičević et al., 2014b) in a form of public presentations of project aims and objectives in the local community (Figure 8).

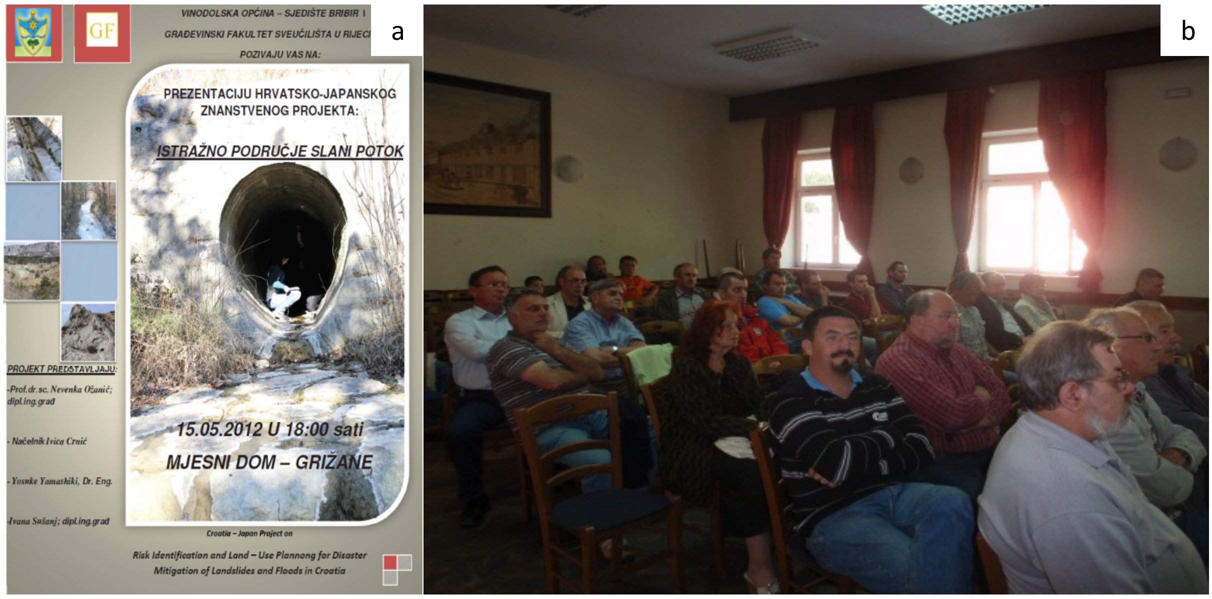


Figure 8: Pubic presentation of Project aims and objectives to local population at Dubračina catchment area (a) Information flyer (b) Public event

The survey consisted of 16 questions regarding flash flood and erosion risk awareness, ways of information exchange, knowledge about mitigation and protection measures from floods and erosion, etc. Overall 25 participants were involved in research where the target research group was the local population that is not employed by government or some sort of media and are not in a possibility to be directly at the source of information (Dragičević et al., 2014b). Within this thesis several questions from this research are elaborated, for more information see paper Dragičević et al. (2014b).

Participants were asked to define the time period when they last received some information related to local problems of flash flood and erosion. 20% of participants came upon this kind of information sometime within the last year while the surprising result was that more than 36% couldn`t remember the last time they received such information.

That itself is undoubted evidence of lack of information exchange in this area and within the community regarding this topic. The local population that remembered the information was asked to name in which form was that information available to them (Figure 9). A most used way for information exchange were stories and tales passed from older generations to younger ones, mainly within families. However, all the information sources were present, most of them in same small percent (Figure 4).

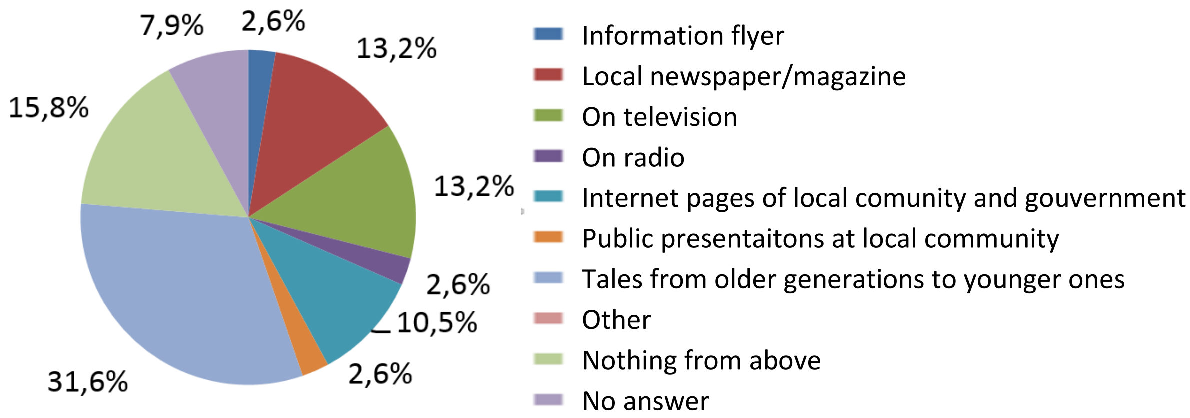


Figure 9: Statistical analysis of answers to the question “In which form were the information about local problems of flash flood and erosion available to the local population?” (Dragičević, et.al., 2012)

Although, there is a lack of information exchange, the knowledge of the local population regarding flash flood and erosion mitigation and prevention measures is pretty good. They were asked to try to recognise some of them and the results showed that the most familiar measures are river regulation and removal of sediment from a water bed. Besides these two, all given measures (listed in the Water Management Strategy, 2009 and Croatian Water Act NN 153/09, 2009) were recognised in some small percent.

One of the most important information that can provide the overall picture of the state of preparedness of local population for hazard events is their awareness on problems and potential hazard risk regarding flash flood and erosion in the local area. The results regarding people erosion awareness on the research area is little less than 50% of investigated population, but other 50% was not. The answer to that can be found within the earlier mentioned problem regarding information exchange within the community, local government and local population.

CHAPTER 4: CHOOSING THE MODEL FOR SOIL EROSION SEDIMENT PRODUCTION ASSESSMENT

The soil erosion and the investigation on erosion processes have been the topic of the scientific research for many decades and is still an ongoing topic with a focus on soil erosion processes and its modelling (Thiemann, 2006). In recent decades there has been a significant development of erosion assessment methods that simultaneously followed the development of computer technologies, as well as Geographic Information Systems (GIS) and Satellite Imagery, thus enabling more detailed information about topography, land use and vegetation cover, as well as broaden the possibilities for the application of more demanding erosion analysis. The concept behind these models differs extremely, wherein each model integrates different scientific methods and modelling approaches (Thiemann, 2006).

4.1 Erosion assessment methods classification

Various models are currently being applied for erosion sediment assessment. There are several classifications of these models available, but the most widely spread and used classification is the one that classifies models on:

a) empirical or regression models,
b) conceptual models and
c) physics-based models.

"***Empirical models*** *are a simplified representation of natural processes based on empirical observation. They are based on observations of the environment and thus, are often of statistical relevance. Empirical models are frequently utilised for modelling complex processes and, in the context of erosion and soil erosion particularly useful for identifying the sources of sediments*" (Thiemann, 2006).

"***Conceptual models*** *are a mixture of empirical and physically based models and their application is, therefore, more applicable to answer general questions. These models usually incorporate general descriptions of catchment processes without specifying process interactions that would require very detailed catchment information. These models, therefore,* *provide an indication of quantitative and qualitative processes within a watershed*" (Thiemann, 2006).

"***Physically based*** *models represent natural processes by describing each individual physical process of the system and combining them into a complex model. Physical equations hereby describe natural processes such as stream flow or sediment transport*" (Merritt et al., 2003). *"This complex approach requires high resolution spatial and temporal input data. Physically-based models are therefore often developed for specific applications, and are typically not intended for universal utilisation. Physically-based models are able to explain the spatial variability of most important land surface characteristics such as topography, slope, aspect, vegetation, soil as well as climate parameters including precipitation, temperature and evaporation*" (Thiemann, 2006).

However, the distinction between the models is not always directly visible and can, therefore, be somewhat subjective, since some models are likely to contain a mix of modules from each erosion model category (Merritt et al., 2003).

Constraints and insufficiently precise results of these models (empirical, conceptual and physic-based) indicated the need to explore more holistic approaches in modelling erosion processes and sediment production. As a result, models that combine descriptive and quantitative procedures that describe the area of interest were explored but received only limited attention in the international scientific literature. Overall, it can be said that another classification of erosion models classify models as qualitative, quantitative and semi-quantitative models (de Vente, 2009; de Vente and Poesen, 2005; Morgan, 2005).

"***Qualitative model*** *can contain various forms of information and has reasoning and learning ability. The structure and behaviour of the actual system are described in an abstract form, focusing on the causality and not on mathematical equations*" (Yan et al., 2013).

"***Quantitative models*** are more precise and specific about a system, but require a large effort in model construction especially if dynamical aspects are included. In a complex system of only a modest number of variables and interconnections any attempt to describe it completely and measure the magnitude of all links would be the work of many people for years. Because of this very often natural systems remain only partially specified and one possible approach to their description and analysis comes from qualitative modelling" (Bondavalli et al., 2009).

"<u>Semi-quantitative</u> *models are a combination of descriptive and quantitative procedures that describe a drainage basin and result in quantitative or sometimes qualitative estimate of sediment yield in a basin. Low data requirements and the fact that practically all significant erosion processes are considered makes semi-quantitative models especially suited for estimating off-site effects of soil erosion. These models benefit from a more quantitative description of factors used to characterise the basin"* (Mahmoodabadi, 2011).

These two model classification are often referred in research and review articles by various authors. However, one interesting classification referring to water erosion models has been given by Karydas et al. (2014) who differs models by their geospatial characteristics (spatial scale, temporal scale and spatial methodology type). For each of the geospatial characteristics, two classes have been proposed (see figure 10). The classification of a water erosion model is based on assigning three classes, each one referring to one of the models geospatial characteristics.

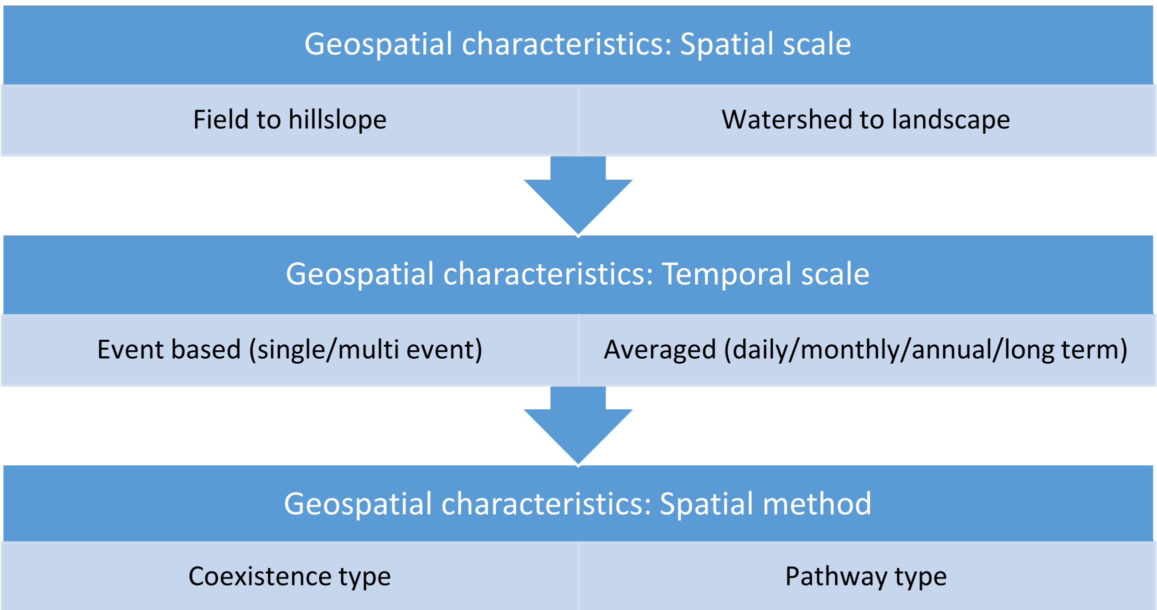


Figure 10: Classes used in water erosion model classification proposed by Karydas et al. (2014)

Within this thesis, the author has adopted the model classification that differs quantitative, qualitative and semi-qualitative models.

4.2 Previous research related to erosion assessment method selection

Water erosion models differ not only in the output information they provide (e.g. erosion sediment production, sediment transportation and/or erosion intensity) but also in terms of complexity, a process considered and the data required for model calibration and model use. There are several papers that deal with the application of various erosion assessment methods depending on the needed scale (de Vente and Poesen, 2005; de Vente, 2009; Blinkov and Konstadinov, 2010) (from global to catchment size), erosion type (gully, rill, bank, sheet) (Blinkov and Konstadinov, 2010) and their assessments by criteria such as prediction accuracy, erosion processes, needed data and calibration (de Vente et al., 2013).

According to Merritt et al. (2003) till today there hasn't been a model that best fits all catchments and all purposes but when choosing a model one needs to consider the initial purpose of the model and the catchment characteristics among other factors affecting the model selection such as:

- Input data requirements of the model
- Spatial and temporal variation of model inputs and outputs
- The accuracy and validity of the model including its underlying assumptions
- The components of the model, reflecting the model capabilities
- The objectives of the model user, including the ease of use of the model, the scales at which model outputs are required and their form
- Hardware requirements of the model.

When facing with the need to choose the appropriate method with an aim to achieve the given set of goals, the first step is to define an existing or individual set of procedures/steps that will lead to the most appropriate solution – the best method for a given case study.

In most cases this procedures starts with choosing the area of interest for the research. After an area of interest is chosen and the problem and research aims for the chosen area are defined, the researcher needs to conduct a detailed investigation on the system to be modelled. As a result, a list of potential models is generated upon which various statistics are calculated and one model is chosen as the most appropriate. Also one can choose with a help of already available model-selection statistics such as Akaike`s information criterion (AIC) (Akaike, 1998) or even Bayes` information criterion (BIC) (Schwarz, 1978). After the model has been selected, if a problem arises, the same model can be modified or the second best model can be chosen (Chatfield, 2006). Some authors suggest the application of several models at once to avoid the limitation to one model that is considered best. Such approach is used in

Bayesian model-averaging technique where the results obtain by different models are compared. The advantage to this approach is in the scenario analysis that allows the institutions to make contingency plans based on different assumptions and taking a weighted average of outputs obtained by different models (Chatfield, 2006).

The procedure shown in section 4.3 is oriented to choose the “best” fitted method for a specified research aims and defined catchment area.

4.3 Considered models and parameter significance

Within this chapter twenty-two different erosion assessment models are analysed (Table 1) and compared with the purpose to define the relevance of each used parameter, better understanding of erosion processes, as well as to give future guidance for simplifying the procedure of choosing the appropriate model based on available data and relevant parameters. Models encompassed with this analysis are (de Vente and Poesen, 2005; de Vente, 2009; Blinkov and Kostadinov, 2010; Jetten et al., 1999.; Kale and Vadsola, 2012; Petkovšek, 2000; Sadeghi et al., 2012; de Vente et al., 2013; Le Gouée et al., 2011, Morgan, 2001; Grimm et al., 2002):

- Pacific Southwest Inter-Agency Committee (PSIAC),
- PSIAC adapted version,
- The vegetation-surface material-drainage density (VSD),
- Erosion Potential (Gavrilović) Method (EPM),
- Factorial Scouring Model (FSM),
- Erosion hazard units (EHU),
- Soil Loss Estimation Model for Southern Africa (SLEMSA),
- CORINE erosion risk maps,
- Coleman and Scatena scoring model (CSSM),
- Fleming and Kadhimi scoring model (FKSM),
- Wallingford scoring model (WSM),
- Universal Soil Loss Equation (USLE),
- Revised Universal Soil Loss Equation (RUSLE),
- RIVM Model,

- INRA Model,
- SCALES Model,
- Fournier,
- Water Erosion Prediction Model (WEPP),
- Soil and Water Assessment Tool (SWAT),
- Morgan-Morgan-Finney (MMF),
- Annualized Agricultural Non-Point Source Pollution (AGNPS) and
- Modified Universal Soil Loss Equation (MUSLE).

4.3.1 Parameter significance

There are forty-four (44) used parameters (Table 5) within these models that can be divided into ten main groups:

- soil,
- climate parameters,
- runoff,
- water network,
- topography,
- vegetation cover and land use,
- upland erosion,
- channel erosion and sediment transport,
- catchment characteristics and
- other.

For each parameter within a group data availability for the Dubračina catchment was explored and noted in the Table 5.

Table 5: List of parameters and associated parameter groups derived from all the models considered in the analysis and its availability for Dubračina catchment

Parameter group:	Parameters:	Available	Partialy available	Unavailable
SOIL	Soil type	+		
	Soil erodibility (texture)	+		
	Potential for soil crust formation			+
	Soil cohesion			+
	Organic matter		+	
CLIMATE PARAMETERS	Descriptive: type of climate with duration of storms and intensity of rain	+		
	Precipitation, erositivity or rain intensity	+		
	Temperature	+		
RUNOFF	Floodplain development			+
	Runoff coefficient		+	
	Flow velocity		+	
WATER NETWORK	Length of the principal waterway	+		
	Cumulated length of secondary waterways	+		
	Main river slope	+		
TOPOGRAPHY	Slope length	+		
	Slope angle	+		
	Average elevation of the watershed	+		
	Descriptive: Possibility for floodplain development depending on the slope			+
	Digital elevation model	+		
VEGETATION COVER AND LAND USE	Percentage of vegetation cover	+		
	Land cover type	+		
	Percentage of cultivated area		+	
	Root mass			+
	Percentage of logging			+

	Percentage of grazing			+
	Road and other construction	+		
	Land cover by crop type			+
	Descriptive: Agricultural practice			+
UPLAND EROSION	Signs of erosion on the catchment	+		
	Coefficient of type and extent of erosion	+		
CHANNEL EROSION AND SEDIMENT TRANSPORT	Descriptive: Type of material, slope gradient and channel size, flow duration and eroding banks	+		
	Sediment delivery signs	+		
	Sediment control measures	+		
	Particle size distribution			+
CATCHMENT CHARACTERISTICS	Catchment shape	+		
	Catchment size	+		
	Perimeter of the watershed	+		
	Distance to water course	+		
	Drainage density	+		
OTHER	Human occupation: density and type of settlement	+		
	Disturbance period		+	
	Shear stress			+
	Shear strength			+
	Roughness			+

The most used parameters (Figure 11) are precipitation, erosivity or rain intensity (72.7%) along with slope angle (72.7%). They are flowed by soil erodibility (68.2%), land cover (50.0%) and percentage of vegetation cover (40.9%) and together form top five parameters. However, since soil erodibility is actually derived from soil type (22.7%) and land cover along with percentage of vegetation cover, agricultural practice and percentage of cultivated area all represent land use/cover, it is hard to separate one parameter from the other and define one more relevant then the other. That is why the overall use of parameter within a group is derived and shown in the Figure 12.

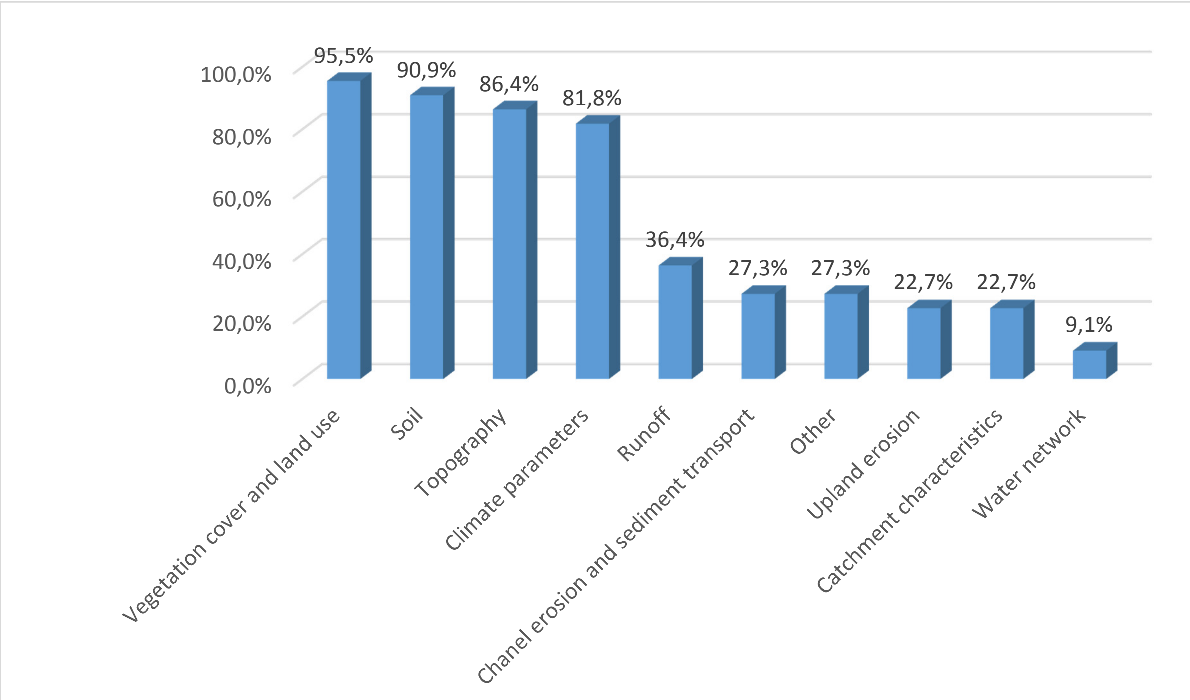


Figure 11: Top ten most used parameters in a method

By group statistic, where at least one of the parameters in a group is used in each method (Figure 12), vegetation cover and land use can be considered the most significant one, with the use percentage (Table 3) of 95.5%, followed by soil with 90.9%, topography with 86.4% both by soil and topography groups with 86.36% and climate and precipitation with 81.8%. There is a minimum gap of 45% between the use of first four group parameters and the rest of the groups (e.g. Runoff is fifth by 36.4%).

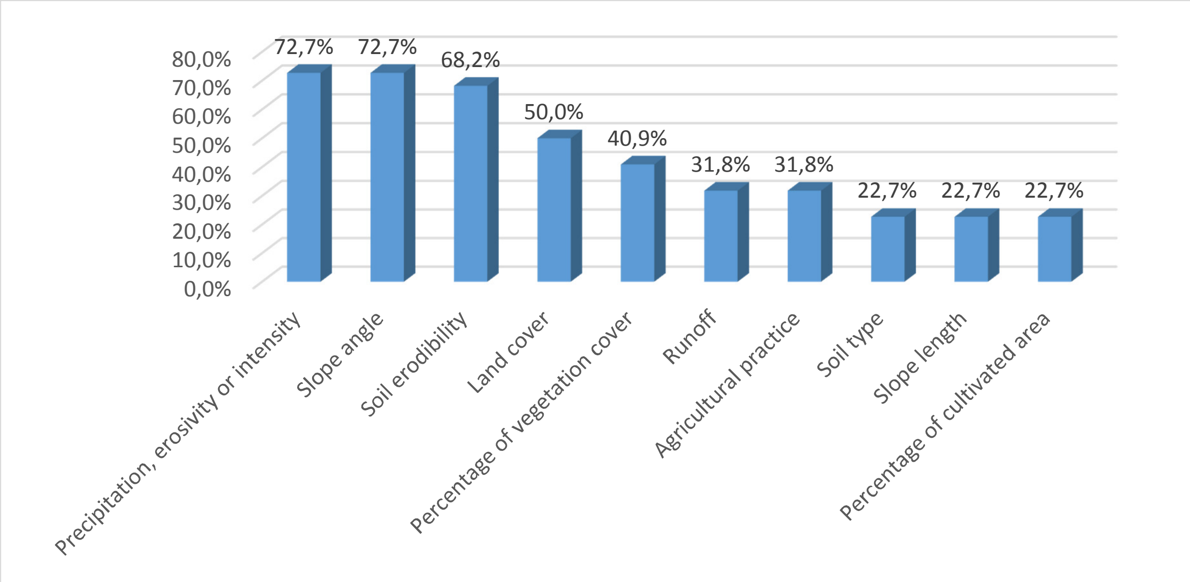


Figure 12: The representation of each parameter group within the selected methods

Taking into consideration the conducted analysis and complementing it with the knowledge about erosion processes, obtained from the literature and described in more detail in Chapter 2, parameter significance can be concluded. Since, rainfall is considered the most important detaching agent and erodibility and type of the soil define susceptibility of the soil to detachment, these parameters can be considered the most important ones. When detached, soil is transported further by erosion agents (e.g. running water) during which topography (e.g. slope angle) has a major impact on the distance, speed and pathways for the runoff and sediment transport, imposing this parameter as relevant when making methodology selection. Agricultural practice, the growth cycle of the plants, % of vegetation cover, the constructions sites, excavation of mineral resources, from vegetation cover and land use group. If not managed properly, this criterion can contribute to the increase of erosion detached sediment, and therefore needs to be taken into consideration (Morgan, 2005; Edwards and Owens, 1991; Cerdan et al., 2002).

According to de Vente (2009) when describing erosion and sediment transport most used parameters in most models are land use, slope, precipitation amount and intensity, runoff and peak runoff rates, runoff shear stress, soil cohesion and surface roughness. When choosing a model or developing a new one for the same purpose it is not always possible and in many cases is extremely difficult to assess all those parameters. Most of these parameters are space and time-variant and dependent upon each other with adds to its complexity and accessibility.

In the following section the methodology for the erosion assessment method selection used in this thesis is described in more detail.

4.4 Methodology for the erosion assessment method selection

The first step to predict erosion and its severity on the area of interest is choosing the methodology to apply. The restrictions of scale applicability of a method, and type of erosion the method deals with, has already been covered within literature (de Vente, 2009; de Vente and Poesen, 2005; Blinkov and Konstadinov, 2010). The accessibility of a data is often the crucial factor in the process of method selection which is why this criterion is considered as one of the most relevant criteria in proposed and applied methodology (Figure 13). Most models focus on a limited number of soil erosion and sediment transport processes analysing only rill and interrill erosion or gully and bank erosion. Till today, there has not been a model that considers all these processes together and can be applied on the catchments with the area of 30 km^2 or more with satisfying results (de Vente, 2009). Natural complexity, spatial heterogeneity and the lack of available data are the main reason for that.

The first step, after the preliminary research, information gathering and the research aims and goals for the area of interest has been defined, is to compose the primary list of existing erosion models as a starting point in the process of appropriate method selection. Upon that, four main criteria are applied

(i) Erosion type,
(ii) Data availability,
(iii) Scale and
(iv) Parameter significance

each leading to a new and reduced list of potential erosion models. The first list reduction is made by applying the erosion type (gully, sheet,…) criteria, where the erosion processes encompassed in remained model list correspond to the erosion processes (erosion type) in a research area. Upon that, the second criteria, previously mentioned, data availability is applied as a two-step process: (i) the first leading to the list reduction to one of the model classification group and (ii) the second leading to the list reduction to model for which all input parameters are available. For each remained method in a list output resolution /scale is defined where the advantage is given to the models providing more detailed resolution. The fourth criterion is parameter significance whose purpose is to define if all significant parameters /parameter groups are included in selected method and potentially indicate future model modification elements if that need arises. This is especially important if new models are used for which the verification hasn`t been conducted. It is necessary to take into consideration all four criteria named above in order to make the best model selection.

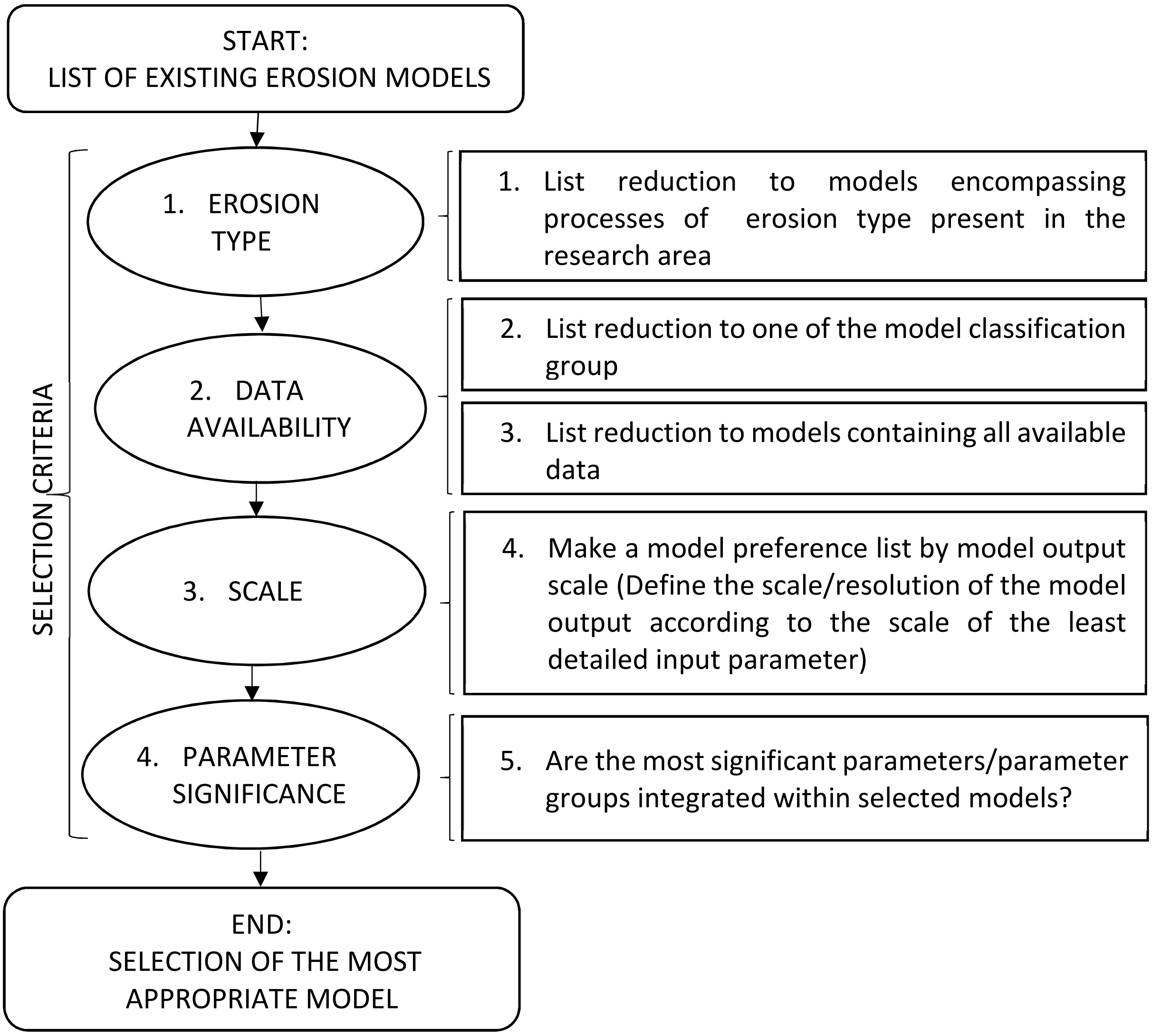


Figure 13: Methodology selection flowchart

4.5 Application of the proposed methodology for method selection

The research area for which erosion assessment is needed, Dubračina catchment, was described in more detail in Chapter 3. Due to the limited number of measured parameters and available data, as well as the lack of previous detail research on erosion processes in the area of interest (Dubračina catchment), in the remainder of this chapter only semi-quantitative models shall be considered. The Pacific Southwest Inter-Agency Committee (PSIAC), the

Factorial Scoring Model (FSM), the Vegetation-Surface Material-Drainage Density Model (VSD), the Gavrilović Model (EPM), Erosion Hazard Units (EHU), CORINE erosion risk maps, the Coleman & Scatena Scoring Model (CSSM), the Fleming & Kadhimi Scoring Model (FKSM), and the Wallingford Scoring Model (WSM) are all examples of semi-quantitative models whose basic description and comparison have been given by de Vente (2009, de Vente and Poesen 2005). A full list of semi-quantitative potential erosion models considered for Dubračina catchment is given in section 4.3 of this chapter. After a detailed overview of the models including gully erosion processes the list was reduced to ten (10) available methods (Erosion Potential (Gavrilović) method, VSD, FSM, PSIAC, PSIAC adapted version, CSSM, WSM, INRA, SCALES and MMF).

Table 6: List reduction after each applied selection criteria

CRITERIA:	**1. EROSION TYPE**	**2. DATA AVAILABILITY**	**3. SCALE**	**4. SIGNIFICANT CRITERIA INCLUDED**
Erosion method:	**(Gully erosion)**		**[cell size in m]**	
Erosion Potential (Gavrilović) Method	**YES**	**YES**	**100x100**	**YES**
VSD	**YES**	**YES**	**100x100**	NO
FSM	**YES**	**YES**	**100x100**	NO
PSIAC	**YES**	NO		
PSIAC adapted version	**YES**	NO		
CSSM	**YES**	NO		
WSM	**YES**	NO		
INRA	**YES**	NO		
SCALES	**YES**	NO		
MMF	**YES**	NO		
EHU	UNKNOWN	YES		-
SLEMSA	UNKNOWN	YES		-
CORINE	NO	YES		-
FOURNIER	NO	YES		-
USLE	NO	NO		
RUSLE	NO	NO		
MUSLE	NO	NO		
FKSM	NO	NO		
RIVM	NO	NO		
WEPP	NO	NO		
SWAT	NO	NO		
AGNPS	NO	NO		

Ten methods mentioned earlier take into consideration gully erosion processes, while in two other, EHU and SLEMSA, the application according to the erosion type is unspecified within available scientific literature known to the author, which is why they were not considered in the further selection process.

When applied the criteria available data for the Dubračina catchment (Table 6) the list of models has narrowed once again (Table 6) to following models: Erosion Potential Method, VSD and FSM. All three remaining methods can produce output maps with 100x100 m cell size resolution. Among them only Gavrilović method can give three different model outputs those being the erosion intensity as an indication of erosion process in the catchment, annual erosion sediment production and transported annual erosion sediment yield. Remaining two methods provide only annual sediment yield and are thus removed from the list. The chosen method, the Erosion Potential (Gavrilović) Method, has been developed for catchments with karstic terrain and torrential rivers, as well as taking into consideration the previously mentioned significant parameter groups, all of which are available and correspond to the Dubracina Catchment.

CHAPTER 5: A REVIEW OF THE EROSION POTENTIAL (GAVRILOVIĆ) METHOD APPLICATION

In this chapter, a detailed overview of the Erosion Potential (Gavrilović) Method (EPM) implementation for erosion intensity and sediment assessment, as well as conclusions and suggestions for future development and improvement of the method and its application is provided.

5.1 Erosion Potential (Gavrilović) Method

The Erosion Potential Method, also known as the Gavrilović method (EPM), was developed by Slobodan Gavrilović and was based on erosion field research in the Morava River Catchment area in Serbia in the 1960`s (Gavrilović, 1972). This method was based on the Method for the Quantitative Classification of Erosion (MQCE), formally developed in 1954, which later became a part/segment of today`s version of the Gavrilović method. During his research, Gavrilović discovered the possibility of further development of the Method for the Quantitative Classification of Erosion (MQCE) used for defining the erosion intensity. Extensions of this method were directed towards the quantification of erosion processes by assessing the sediment transported downstream that reaches the control profiles (Amini et al., 2010).

The method encompasses erosion mapping, sediment quantity estimation, and torrent classification. Since 1968, the method has been extensively applied to erosion and torrent-related problems in the Balkan countries (Dragičević et al., 2014a; Gavrilovic et al., 2008). It is currently being applied worldwide, from Croatia, Serbia, Slovenia, Italy, Macedonia, Bosnia and Herzegovina, Montenegro, Iran to Chile (references are given in Table 13).

The most often calculated outputs of the method (equations 1-8, Table 5) are (i) the total annual volume of detached soil W_a (equation 1, Table 5), (ii) the erosion coefficient (Z) (equation 3, Table 5), and (iii) the actual sediment yield G_y (equation 7, Table 7). ***The total annual volume of the detached soil*** *can be defined as the soil available for detachment over a year in cubic metres due to the action of erosion agents and local area characteristics.* ***The erosion coefficient*** *is a dimensionless parameter that defines erosion severity or erosion intensity through both numerical and descriptive classification of its values and can be viewed as an erosion risk indicator* (Dragičević et al., 2014a). ***The actual sediment yield*** *in* m^3*/year* *refers to sediment transportation through a river network measured at the tow of the catchment as a result of sediment transportation (*Kazimierski et al., 2013*).*

Table 7: Equations and description of the parameters for the Gavrilović method (de Vente and Poesen, 2005; Gavrilović, 1972)

$W_a = T * P_a * \pi * \sqrt{Z^3} * F$	(1)	W_a	Total annual volume of detached soil [m^3/year]
		T	Temperature coefficient [-]
		P_a	Average annual precipitation [mm]
$T = \sqrt{\frac{T_0}{10} + 0.1}$	(2)	Z	Erosion coefficient [-]
		F	Study area [km^2]
		T_0	Average annual temperature [^{o}C]
$Z = Y * X_a * (\phi + \sqrt{J_a})$	(3)	Y	Soil erodibility coefficient [-]
		X_a	Soil protection coefficient [-]
$\xi = \frac{\sqrt{O * z}}{(l_p + 10)} * D_d$	(4)	ϕ	Coefficient of type and extent of erosion [-]
		J_a	Average slope of the study area [%]
		ξ	Sediment delivery ratio [-]
$D_{d.original} = \frac{1}{0.25} = 4$	(5)*	O	Perimeter of the watershed [km]
		z	Mean difference in elevation of the watershed [km]
$D_{d.modified} = \frac{l_p + l_a}{F} = \frac{L}{F}$	(6)**	D_d	Drainage density [km/km^2]
		l_p	Length of the principal waterway [km]
$G_y = \xi * W_a$	(7)	l_a	Cumulated length of the secondary waterways [km]
		L	Cumulated length of the principal and the secondary waterways [km]
		G_y	Actual sediment yield [m^3/year]

* Originally set as a constant value, continues to be applied in various research

** Modification of the method made by Lazarević (Tosic and Dragicevic, 2012), applied today in various studies

According to de Vente (de Vente, 2009; de Vente and Poesen, 2005), this method can be characterised as a semi-quantitative method because it is based on a combination of descriptive and quantitative procedures. However, of all the available semi-quantitative methods named in the introduction, this method is the most quantitative because this method uses a descriptive evaluation of only three parameters: soil erodibility; soil protection, which represents land use/cover and type; and extent of erosion in the catchment. All other parameters represent quantitative catchment descriptors. Table 6 shows the procedure for the evaluation of three method parameters that are defined using the descriptive attributes of the analysed catchment/cell.

Table 8: Descriptive evaluation of Gavrilović method parameters (de Vente and Poesen, 2005; Haghizadeh et al, 2009)

Soil protection coefficient [X_a]	
Mixed and dense forest	0.05-0.2
Low density forest with grove	0.05-0.2
Coniferous forest with little grove, scarce bushes, bush prairie	0.2-0.4
Damaged forest and bushes, pasture	0.4-0.6
Damaged pasture and cultivated land	0.6-0.8
Areas without vegetal cover	0.8-1.0
Soil erodibility coefficient [Y]	
Hard rock, erosion resistant	0.2-0.6
Rock with moderate erosion resistance	0.6-1.0
Weak rock, schistose, stabilised	1.0-1.3
Sediments, moraines, clay and other rock with little resistance	1.3-1.8
Fine sediments and soils without erosion resistance	1.8-2.0
Coefficient of type and extent of erosion [ϕ]	
Little erosion on watershed	0.1-0.2
Erosion in waterways on 20-50% of the catchment area	0.3-0.5
Erosion in rivers, gullies and alluvial deposits, karstic erosion	0.6-0.7
50-80% of catchment area affected by surface erosion and landslides	0.8-0.9
Whole watershed affected by erosion	1.0

5.2 Modifications to the Erosion Potential (Gavrilović) Method

One of the first upgrades to the method was proposed by Lazarević (1985), who noted in his work the need to adjust the assigned values for parameters describing the coefficient of type and extent of erosion ϕ, the soil protection coefficient X_a, representing land use and soil erodibility coefficient Y (Table 8). These three parameters, along with the slope angle, form the erosion coefficient Z. The purpose of this modification was to transform the definition of the erosion coefficient from its original meaning as soil erodibility to today`s version as erosion intensity. Lazarević also modified the table for the classification of the erosion intensity represented by the erosion coefficient Z (Table 9) (Lazarević, 1985).

Table 9: Descriptive and numerical evaluation of erosion coefficient Z as erosion intensity indicator

Descriptive evaluation	***According to original author, Gavrilović (1972)***		***Simplified version used today***
	Erosion depth	**Numerical evaluation**	
Excessive erosion	deep	≥ 1.51	>1.00
	mixed	1.21 – 1.50	
	surface	1.01 – 1.20	
Severe erosion	deep	0.91 - 1.00	0.70 - 1.00
	mixed	0.81 - 0.90	
	surface	0.71 - 0.80	
Medium erosion	deep	0.61 - 0.70	0.40 - 0.70
	mixed	0.51 - 0.60	
	surface	0.41 - 0.50	
Slight erosion	deep	0.31 - 0.41	0.20 - 0.40
	mixed	0.25 - 0.30	
	surface	0.20 - 0.24	
Very slight erosion	deep mixed surface	0.01 - 0.19 or less	0 - 0.2

Tošić and Dragićević (2012) continued the work of Lazarević. They proposed a new methodology for determining the erosion coefficient (Z) adapted for use in GIS environments that is based on the empirical methodology of Gavrilović and its extensions by Lazarević. The main essence of their work poses the use of a PDA (Personal Digital Assistant) device with an integrated GPS and GIS receiver. The use of the device was combined with appropriate software, namely, ArcPad, to merge the GPS with the GIS. The aim was to directly determine the coefficient of type and extent of erosion [ϕ] on site and transform the data accordingly to the erosion parcel condition. In addition to this research, regression analysis based on 3257 erosion plots from the Drenova reservoir basin and 28,249 erosion plots from the Republic of Srpska considered the relationships among the erosion coefficient and its parameters [Y, X_a, ϕ and J_a] and indicated a strong correlation between the erosion coefficient and average slope of the study [J_a].

Another modification was proposed by Globevnik et al. (2003), who suggested values for the soil protection coefficient based upon Corine land cover classification (Table 8). Later, Fanetti and Vezzoli (2007) suggested a change in the categorisation of the soil protection coefficient X_a based on different land use categories (Table 10) and were the first to consider urban areas as areas of potential erosion, therein assigning them a value of greater than 0. They included several stages of urbanisation as well as various vegetation types, from growing cultures to pastures and forests.

Table 10: Suggested modifications for evaluation of Soil protection coefficient X_a

By Globevnik et al. (2003)	
Land cover classification	***X_a***
Artificial surfaces, Inland water	0
Broad-leaved forest, Mixed forest	0.05
Heterogeneous agricultural areas	0.4
Transitional woodland shrub	0.5
Pastures, Natural grassland	0.6
Permanent crops	0.7
Arable land	0.9
Bare rocks, Areas under erosion	0.95
By Fanetti and Vezzoli (2007)	
Land use categories	***X_a***
Scattered urbanisation	0.05
Rare urbanisation, copse broad-leaved wood	0.1
Discontinuous urbanisation	0.15
Continuous urbanisation	0.18
Dense urbanisation, copse broad-leaved and coniferous wood	0.2
Coniferous wood	0.4
Meadow and pasture with isolate arboreous elements	0.5
Meadow and pasture	0.6

Fanetti and Vezzoli (2007) also proposed a different categorisation for the soil erodibility coefficient Y (Table 12), which they applied to the Greggio river catchment in Italy. They divided the parameter that describes erodibility (Y) into three categories that describe moderate erosion resistance, little erosion resistance and very little erosion resistance. They divided the slope angle parameter for the Greggio river catchment in Italy into five categories (Table 11), namely, 0-10%, 10-20%, 20-40%, 40-60% and 60-80%, but omitted a suggestion for the assessment of slopes steeper than 80%.

Table 11: Suggested modifications by Fanetti and Vezzoli (2007) for the evaluation of Average slope of the study area

Average slope angle	J_a
0-10%	0.05
10-20%	0.15
20-40%	0.3
40-60%	0.5
60-80%	0.7

Table 12: From original to some suggested modifications for the Soil erodibility coefficient *Y*

Soil type	*Y*
By original author Gavrilović (1972)	
Sand, granule schist	2.0
Loess, tuff, salty soil, steeply soil	1.6
Wathered limestone and marl	1.2
Red sandstone, serpentine, flysch	1.1
Clastic schist, mica schist, gneiss	1.0
Hard doll stone	0.9
Mountain soils	0.8
Black hydro morph soils	0.6
Rock with moderate erosion resistance, alluvium	0.5
Hard rock, erosion resistant	0.25
By Lazarević (1985)	
Hard rock, erosion resistant	0.1-0.3
Rock with moderate erosion resistance	0.3-0.5
Weak rock, schistose, stabilised	0.5-0.6
Sediments, moraines, clay and other rock with little resistance	0.6-0.8
Fine sediment and soils without erosion resistance	0.8-1.0
By Fanetti and Vezzoli (2007)	
Limestone: moderate erosion resistance	0.8
Alluvial deposit: little erosion resistance	1.3
Glacial deposit: very little erosion resistance	1.6

5.3 Review of the Erosion Potential (Gavrilović) Method Application

This paper summarises the application of the Gavrilović method from analysing more than fifty different papers from relevant scientific bases that were available to the author of this thesis, therein estimating the erosion risk/intensity as well as sediment production and transportation on more than fifty different catchments worldwide (Table 13).

Table 13: Overview of the Gavrilović method application

PAPER	CATCHMENT			CALCULATED OUTPUTS OF GAVRILOVIĆ METHOD			DRAINAGE DENSITY D_d	
				Wa	*Gy*	Z^{**}		
	NAME	COUNTRY	SIZE	m^3/km^2	m^3/km^2	/	$\frac{L}{F}$	$\frac{1}{0.25}$
Bagherzadeh and Daneshvae, 2010 and 2011	KARDEH	IRAN	555	266	N/A	-	-	-
Globevnik et al., 2003; Zorn and Komac, 2011; Petkovšek, 2002	ROKAVA (DRAGONJA)	SLOVENIA	91/20.4	50	N/A	-	-	-
Globevnik et al., 2003; Petraš et al., 2003	JUKANI (BOTONEGA)	CROATIA	26.7	1070	399.47	-	-	+
Globevnik et al., 2003	RAŠA	CROATIA	205	1270	N/A	-	-	-
Haghizadeh et al., 2009	UPPER SEZAR RIVER	IRAN	344.91	15299.84	15483.13	-	-	+
Milevski et al., 2008; Blinkov et al., 2010	UPPER PART OF BREGALNICA	REPUBLIC OF MACEDONIA	1124.7	925	N/A	-	-	-
Solaimani et al., 2009a and b	NEKA	IRAN	N/A	144465.1; 15542.9	N/A	-	-	-
Tazioli, 2009	MUSONE	ITALY	374	700.5	N/A	-	-	-
Tazioli, 2009	ESINO	ITALY	1223	621.4	N/A	-	-	-
Zorn and Komac, 2009; Zorn et al., 2007	UPPER SOČA	SLOVENIA	591.5	8047-9670	N/A	-	-	-
Fanetti and Vezzoli, 2007	GREGGIO	ITALY	6.1	640	465	-	+	-
Tosic and Dragicevic, 2012	REPUBLIC OF SRPSKA	BOSNIA AND HERZEGOVINA	N/A	N/A	N/A	N/A	-	-
Solaimani and Modallaldoust, 2008	JAM AND RIZ	IRAN	909.19	2327.4	N/A	-	-	-
Amini et al., 2010	EKBATAN DAM	IRAN	218	942.29	810.37	-	-	+
Tangestani, 2006	AFZAR	IRAN	800	556	N/A	-	-	-
Deilami et al., 2012	KAROON	IRAN	27694.8	8374.78	1507.4	-	-	+

Gavrilovic et al., 2013	PLOTS IN SERBIA	SERBIA	N/A	N/A	N/A	N/A	-	-	
Kouhpeima et al., 2011	AMROVAN	IRAN	1023	5.10	N/A	-	-	+	
Kouhpeima et al., 2011	ATARY	IRAN	6.27	7.17	N/A	-	-	-	
Kouhpeima et al., 2011	ALI ABAD	IRAN	1.29	5.4	N/A	-	-	-	
Kouhpeima et al., 2011	EBRAHIM ABAD	IRAN	5.07	1.25	N/A	-	-	-	
Kouhpeima et al., 2011	ROYAN	IRAN	5.39	7.30	N/A	-	-	-	
Ghazavi et al., 2012	N/A	N/A	N/A	N/A	N/A	-	-	-	
Barmaki et al., 2012a, b	KHIAV CHAY	IRAN	800	2237.49 (1968); 12252.44 (2007)	N/A	-	-	-	
Sadoddin et al., 2008	RAMIAN	IRAN	240	N/A	N/A	+	-	-	
Konstadinov et al., 2008	VRANJSKO-BANJSKA	SERBIA	150	2936 (1956); 1050 (2007)	2123 (1956); 759.50 (2007)	-	-	-	
Ristic et al., 2012	KALIMANSKA	SERBIA	16.04	3775 (1927); 533.17 (2010)	2494.45 (1927); 350.7 (2010)	-	+	-	
Amiri et al., 2012	GHARA-AGHCH	IRAN	89.62	N/A	N/A	+	-	-	
Abadi and Ahmadi, 2011	KASILIAN	IRAN	68	N/A	N/A	+	-	-	
Ghobadi et al., 2011	IMAMZADE ABDULLAH BAGHMALAK	IRAN	105	370.08-3481.25	418.19	-	-	+	
Ristic et al., 2011a	JELAŠNICA	SERBIA	30.04	910.82	397.12	-	-	-	
Bemporad et al., 1997	PRESCUDIN	ITALY	16	N/A	N/A	+	-	-	
Ristić et al., 2011b	MANASTIRICA	SERBIA	29.93	813.8	425.6	-	-	-	
Ristić et al., 2011b	KAMIŠNA	SERBIA	26.94	741.4	375.9	-	-	-	
Sekularac et al., 2012	RUJEVAC	SERBIA	0.89	259.2	60.36	-	-	-	
Sekularac et al., 2011	VASOVIĆA	SERBIA	2.52	502.6	125.67	-	-	-	
Lakicevic and Srdjevic, 2011	RASINA	SERBIA	N/A	N/A	N/A	+	-	-	
Tosic et al., 2012	UKRINA	BOSNIA AND HERZEGOVINA	1498.48	632.3 (1980); 551.3 (2010)	306.06 (1980); 247.47 (2010)	-	-	+	

Milovanovic, et al., 2011	CELIJE RESERVOIR	SERBIA	609.15	1189 (1960); 586 (2008)	540(1960); 266 (2008)	-	-	-
Dragicevic et al., 2011	EASTERN SERBIA	SERBIA	17060.1	N/A	N/A	+	+	-
Petraš et al., 2008	ABRAMI (TESNA POLJA)	CROATIA	N/A	20-28	N/A	-	-	-
Gavrilović et al., 2001	COUNTY POŽAREVAC	SERBIA	N/A	100-3000	N/A	-	-	-
Spalevic et al., 2012	ROVACKI	MONTENEGRO	11.7	404.17	117.19	-	+	-
Spalevic et al., 2013a	DJURICKA	MONTENEGRO	69.5	1663.2	645	-	+	-
Spalevic et al., 2013b	POLIMLJE	MONTENEGRO	2200	331.78	N/A	-	+	-
Spalevic et al., 2013b	NAVOTINSKI	MONTENEGRO	8.4	123.79	37	-	+	-
Spalevic et al., 2013c	BOLJANSKA	MONTENEGRO	27.5	1072.15	315	-	+	-
Dragičević et al., 2014a	DUBRAČINA	CROATIA	43.5	250-682	-	-	+	
Kazimierski et al., 2013	BERMEJO	CHILE	N/A	100*	N/A	-	+	-
Kazimierski et al., 2013	PILCOMAYO	CHILE	N/A	108*	N/A	-	+	-
Ballio et al., 2010	TARTANO	ITALY	47	965.34	1126.19	+	+	

*In the following units: Mt/catchment/year

**As only calculated method output derived from the analysis

The most commonly calculated value using the Gavrilović method for 82% of the catchments is the Total annual volume of the soil W_a. The value varies from 50 m^3/km^2/year for Rokava, Slovenia, (Globevnik et al., 2003; Zorn and Komac, 2011; Petkovšek, 2002) to 12,252 m^3/km^2/year for Khiav Chav, Iran (Barmaki et al., 2012a, b). The actual sediment yield, or sediment transported downstream, is given for 38% of the catchments, therein ranging from 37 m^3/km^2/year to 2495 m^3/km^2/year.

A small number of analysed case studies (14% of the analysed catchments) only provide an assessment of the erosion coefficient Z, thus providing insight into erosion severity/intensity for certain catchments but not into the expected sediment production. An example can be found in the paper written by Amiri et al. (2012, 2013). They used the Gavrilović method to determine the soil sensitivity to erosion, which they defined as the Gavrilović erosion severity coefficient Z. This parameter was then further used in the model for defining the suitability of mixed livestock grazing in the Ghara-Aghch region in Iran, where livestock and pastures are the main developing sectors.

Depending on the characteristics of the catchment area, especially the drainage density, final results for the Actual sediment yield can vary from quite small values up to the same values estimated for the Total annual volume of the soil or yearly amount of sediment available for detachment. In no case should the obtained values for the Actual sediment yield result in values that are larger than the values calculated for the Total annual volume of the soil. This is because the estimated sediment that is involved in transport cannot be greater than the sediment available for detachment from the soil for the same period of time. The only case that can lead to such a scenario is if detached soil from a previous period has not in some percentage been transported downstream in the past period and if all the material from the present period is involved in transport, thereby triggering residual sediment from the previous time period to participate in the current period's transport. The described case, however, is not considered within the Gavrilović model, and therefore, such a scenario cannot be foreseen. The described scenario can be found for the Upper Sezar River, Iran, (Haghizadeh et al., 2009) (see Table 13) and is not considered to be accurate. One of the reasons for this outcome is based on the use of a different formula for the Sediment delivery ratio that includes the Drainage density parameter. In the original form of the Gavrilović method, instead of the formula for the Drainage density, a constant value of 4 was used. Later, the model was modified, and the Drainage density was taken as the ratio between the primary and secondary river length and the contributing/catchment area. Results such as those for the Upper Sezar River was obtained using the constant value instead of the length/area ratio. Overall, 37% of catchment results showing Actual sediment yield were based on a constant value for the drainage density coefficient.

5.4 Erosion Potential (Gavrilović) Method, GIS and remote-sensing data

The method was originally based on obtaining one value for each parameter that best represents the entire catchment. It was initially recommended that catchments with strong spatial variability in terms of the parameters included in the Gavrilović method should be divided into sub-catchments that present homogeneous characteristics (Fanetti and Vezzoli, 2007). Today, that division can be somewhat reduced to the cell size due to the development of Geographical Information Systems (GIS). Therefore, it can be said that the evolution of the Gavrilović model began with the use of GIS environments and the integration of spatially distributed input data such as geology, soil and land use parameters. According to Thieken et al. (1999) and Vogt et al. (2003), the reliability of the final results within GIS is strongly correlated with the accuracy and level of detail of input data (topographic, land use, and soil data sources). Newer technologies, namely, areal and satellite remote-sensing data, can be used to provide substantially better detail and therefore simplify the procedure for assessing erosion sediment production and transportation in the area of interest (Fanetti and Vezzoli, 2007). Today, GIS and remote sensing technologies provide an improvement in defragmentation of catchments and sub-catchments to arbitrary cell sizes. For example, Bagherzadeh et al. (2010, 2011) subdivided a catchment into eight homogeneous terrain units based on a visual interpretation of satellite image and field observations. Additionally, Globevnik et al. (2003) analysed the applicability of the Gavrilović method in combination with a GIS technique. Their results demonstrated the decrease in predicted values for sediment production caused by erosion processes if calculated using parameters as a spatially variant, in contrast to the results obtained using the traditional/automatic method/catchment-oriented soil erosion map.

Milevski et al. (2008) (as well as Globevnik et al. (2003)) also demonstrated the decrease in values obtained from spatially variant data (925 $m^3/km^2/year$) compared to values obtained for the entire catchment (977 m^3/km^2/year), which also better corresponded to the measured values. However, the difference between the two obtained results is small, and such differences can be taken as noise within any sediment yield measurement. Among a total of fifty-one (51) analysed catchments, 66% use GIS. In the other papers, the use of GIS is not clear or is not used at all, and 42% use a remote sensing technology for land cover parameter determination.

5.5 Land use/cover change and erosion mitigation measures

Since their development, GIS technologies have enabled the analysis of land use/cover maps in greater spatial detail, and remote sensing technologies have facilitated the generation of new and varied data sources for the same parameter.

Solaimani et al. (2009a, b) analysed the effect of applying the change in land use as an erosion mitigation and land management measure and showed that the output of the model predicts the decrease in erosion sediment yield of 89.24% with the Gavrilović method. Although the authors did not analyse the sensitivity of outputs obtained from the Gavrilović method, this paper is the first to refer to the significant oscillation in the predicted erosion sediment quantities that depend on the change in soil protection coefficient representing the land use component in the Gavrilović model.

Zorn and Komac (2009) and Zorn et al. (2007) noted in their research the decrease of 37% in predicted values for the annual volume of detached soil by erosion processes using the Gavrilović method as a result of applying a different land use map (from the Ministry of Agriculture, Forestry and Food of the Republic of Slovenia) for the year 2000 compared to the one from the year before (1999-cadastre data). They concluded that changing the agricultural area (land use categories and sizes) even by a small percentage leads to significant changes in erosion risk intensity and sediment quantity predictions. Because they analysed erosion changes for five time periods (1827, 1896, 1953, 1979 and 1999), they found historical sources to be of particular use when analysing the change in erosion processes during a period of time in an area of interest. For example, they showed that the decrease in agricultural land by 5% will lead to an 8.5% decrease in the annual volume of detached soil and a decrease of approximately 13.5% in actual sediment yield involved in transport by river network.

Another application of the Gavrilović method in Iran (Solaimani and Modallaldoust, 2008) attempted to define relations between slope gradient and land use to reduce erosion in the Jam and Riz basins. In this research, the slope was divided into seven classes (0-5, 5-10, 10-20, 20-30, 30-40, 40-50, >50 [%]) and assigned an *I*-factor based on average values of the slope category. The authors predicted a decrease in erosion for the entire catchment of up to 58.3% (from 2327.4 m^3/km^2/year to 970.4 m^3/km^2/year) if implementing adequate land use management measures.

The impact of four different biological activities (agro-foresting, tree plantation, seeding and sowing) and 16 different vegetation management scenarios in the Ramian catchments in Iran is analysed by Sadoddin et al. (2008). They compared the results obtained using the Gavrilović method with the results obtained with the Soil Conservation Service (SCS), where they used the determination of the vegetation cover changes of hydrological characteristic (SCS) and soil erosion severity (Gavrilović). One of the objectives was a cost-benefit analysis that demonstrated the economic and social impact upon soil erosion for a time period of 80 years.

Dragičević et al. (2014a) were the first to analyse uncertainties in the magnitude and spatial distribution of annual sediment production predictions in the Dubračina catchment, Croatia, where several alternative land cover/use inputs were applied. They used three different land cover/use data sets: (i) a CORINE land cover map (with a 1:100,000 scale), a Spatial Plan (with a 1:25,000 scale), and a Landsat 8 scene (with a 15x15 m resolution). They demonstrated the sensitivity of the Gavrilović method to different land cover/use inputs. The CORINE land use map gave values that were approximately 3 times smaller than the estimations based on the Landsat 8 data and twice as small as the results based on the Spatial Plan.

Ristic et al. (2012) analysed the effect of changing hydrological conditions by restoring the catchment upon erosion and flood processes to define effective erosion mitigation and protection measures. They compared the outputs from the Gavrilović method for the Kalimanska river catchment in Serbia for two time periods: 1967, before the restoration works, and 2010, after implementing the mitigation measures. The model showed the decrease in the predicted volume of the detached soil as well as for the erosion sediment transported by the river network. The seven-fold decrease in the given values as well as the decrease in erosion severity from excessive erosion to weak erosion can be found in not only the implemented measurements but also the depopulation of the catchment area and abandonment of the agricultural practice.

In another paper, Ristic et al. (2011a) predicted with Gavrilović method a 44.1% decrease in annual sediment production of eroded material if a specific combination of biotechnical, technical and administrative measures were to be implemented in the Jalešnica catchment in Serbia. The same analysis was applied to the sediment transported downstream by a river network, where the predicted decrease was estimated to be approximately 43.6%. Those measures included an improvement of hydrological conditions caused by the change in land use, restoration of degraded agricultural land, limitations of livestock on grazing surfaces and administrative measures defined through the plan for erosion protection and mitigation of the catchment wider area. During their research, they noticed that the land use is closely related to erosion processes and is a key to erosion mitigation and protection. Although technical structures in the riverbed are often applied as erosion and torrent flood mitigation measures, they are not as effective if used as the only measure in the catchment. The same analysis was conducted for the Manastirica and Kamišna catchments in Serbia (Ristić et al., 2011b).

The 40-year change in erosion processes and impact of anti-erosion works on sediment production for the Celije reservoir in Serbia, whose main purpose is as a water supply was analysed by Milovanovic et al. (2011). They concluded that the implemented anti-erosion works, which included technical (more than 30 check dams and contour walls), biotechnical and biological work (afforestation and grassing), led to the decrease in erosion sediment production and transported sediment yields of 49% in 40 years which they calculated with Gavrilović method.

5.6 Other applications of the Erosion Potential (Gavrilović) Method

Lakicevic and Srdjevic(2011) analysed the connection between the social-economic conditions and the erosion processes using Gavrilović method in small catchments in Serbia while Tosic et al. (2012) analysed the anthropogenic influence (demographic changes) on erosion processes in the form of changes in population over time. Both papers concluded that human emigration leading to abandonment of agricultural land leads to a decrease in the intensity of erosion processes and sediment production in that area.

Barmaki et al. (2012a, b) compared the results obtained using the Gavrilović method for two different time periods, namely, 1968 and 2007. They indicated an increase in drainage density of 41% from 1968 to 2007 in the analysed time period due to rill erosion and an increase in agricultural practice caused by an increased population.

Kazimierski et al. (2013) analysed the impact of climate change parameters on the sediment yield production and, based on the Gavrilović method, developed a methodology for the estimation of future sediment yield production for the Upper Plata Catchment in Chile, Bolivia. They noticed a significant difference between the observed and predicted erosion sediment yields, which they associated with inaccurate interpretations of the observed data and deficiencies in the Regional Climate Models, especially those associated with rough resolution scales (50 km). They proposed corrections for the temperature as an input parameter where the input resolution is rough as well as for the area of the Upper Plata Catchment. They generated projections for sediment yield production for up to the year 2100 based on changes in temperature and precipitation without considering the potential changes in land cover/use. The time period from 2011-2040 is taken as a near future, 2041-2070 as an intermediate future and 2071-2100 as a far future. Their analysis did not indicate either a significant change in annual sediment production over time or a relatively small contribution of temperature in comparison to precipitation to the final sediment predictions.

Bemporad et al. (1997) applied the Gavrilović method (annually and monthly based) for the determination of the total volume of detached sediment via erosion processes. When calculating the sediment on a monthly basis, the temperature and the rainfall parameter were varied according to their monthly oscillations, and all other parameters of this method were held constant in time. The disadvantage of this model was in the use of rainfall data from one meteorological station, which was then applied for the entire catchment. According to the authors, when reducing the analysis to the monthly time increment, errors in the rainfall data can be disregarded. They assessed the sediment transport in kg/s, calculated within the hydrological model for water discharge using the equation for sediment continuity and motion by Hrissanthou (not Gavrilović). The authors concluded that the predicted annual sediment production based on the Gavrilović method corresponds to the values obtained for the transported sediment downstream. This was verified through a one-time field observation after a flood in 1992 that filled the newly built retention dam. They assessed that all the sediment that is produced in a period of 12 months can be transported and accumulated in the retention dam. The assessments performed for the monthly data were not validated; thus, further field and calibration data are required. The final results for sediment production and transportation have been presented and made available for the annual assessment as a difference between the transported and produced sediment in kg/s for the time period from 1972 to 1984.

5.7 Comparison of the Erosion Potential (Gavrilović) Method with other erosion assessment methods

The results obtained using the Gavrilović method have been compared with the PSIAC, MPSIAC and RUSLE methods based on all papers at the authors' disposal.

Tangestani (2006) compared the Gavrilović and PSIAC model outputs and obtained a better reliability for the PSIAC model for determining the areas of very high erosion potential compared to the Gavrilović model. A field visual overview with GPS confirmed the good estimation for areas of moderate and heavy erosion with the Gavrilović method and poorer accuracy for areas with slight erosion potential. Another comparison with PSIAC method (Bagherzadeh and Daneshvae, 2010, 2011) showed the same pattern for the predicted sediment yield by both methods with a correlation coefficient of 0.95, which confirmed the method applicability of both methods to semi-arid and arid catchments. Ghobadi et al. (2011) compared the Gavrilović method with PSIAC and MPSIAC and concluded that Gavrilović method is not suitable for weather conditions in Iran and that it provides much less accurate annual sediment production assessments than does the MPSIAC method. In addition, they also used a simplified formula for the sediment delivery ratio in their assessments.

Petraš et al. (2008) compared the results obtained using the RUSLE and Gavrilović methods with on-site observations and concluded that there was a better compatibility of the RUSLE method with on-site data measurements for the Abrami test field (Istria, Croatia).

The Gavrilović method in comparison to some other methods does not explore the physics of erosion processes and as such is advantageous for areas where minimal data are available or where there is a lack of previous erosion research. As such, the method can provide not only the amount of sediment production and sediment transport but also the erosion intensity as the preliminary result and indications or areas of potential erosion threats.

5.8 Field measurement and the Erosion Potential (Gavrilović) Method verification

Out of all the analysed catchments, in only fifteen (15) of them the verification has been mentioned within the paper (Table 14). In these papers different verification methods were applied, depending on available equipment and accessibility of a terrain.

Measurements of the sediment yield on the erosion plots were conducted at the Rokava (Dragonja) river basin in Slovenia (Zorn and Komac, 2011; Petkovšek, 2002) and Jukani (Butonega), Croatia (Globevnik et al., 2003; Petraš et al., 2003). At the Bregalnica basin, Republic of Macedonia (Milevski et al., 2008; Blinkov et al., 2010), a very good correspondence between the results obtained using the Gavrilović method and on-site measurements was obtained. Haghizadeh et al. (2009) and Tangestani (2006) used a comparison of the output results of the model with field observations and a GLASGOD (Global Assessment of Soil Degradation) map as a verification method.

Table 14: Analysed catchments categorised by size

CATCHMENT CATEGORISATION BY SIZE (WFD, 2000/60/EC)	No. OF ANALYSED CATCHMENTS	No. OF CATCHMENTS WITH VERIFICATION OF RESULTS
UNCLASIFIED < 10 km^2	8	0
SMALL CATCHMENTS 10- 100 km^2	14	4
MID-SIZE CATCHMENTS >100-1000 km^2	13	5
LARGE CATCHMENTS >1000-10 000 km^2	5	3
VERY LARGE CATCHMENTS > 10 000 km^2	2	0
UNKNOWN SIZE	9	3
SUMMARISED	51	15

Bagherzadeh and Daneshvae (2010, 2011) verified the model outputs by a field survey using GPS and a visual comparison of areas characterised as areas with moderate and heavy annual sediment yields.

Amini et al. (2010) applied the Gavrilović method to the Ekbatan Dam drainage basin in Iran and concluded that this method can overestimate the sediment yield because it lacks a granulometric structure, humus concentration, the morphology of the slope and runoff parameters that affect erosion processes all of which are usually a part of a physical based model and not empirical such as Gavrilović.

Kouhpeima et al. (2011) analysed five different catchments in Iran and used its comparison to measured sediment deposits in the reservoir as a verification method. The same method was also used in the Prescudin catchment, Italy, (Bemporad et al., 1997) and showed minimal deviation between predicted and measured sediment yield values.

Nuclear probes for suspended-load measurements were used at the Esino and Musone river basin, Italy (Tazioli, 2009). The measurements exhibited some deviations in comparison with the overall sediment yield production estimated with the Gavrilović method but overall obtained a good correspondence concerning sediment yield order of magnitude on a yearly basis. It was concluded that further measurements are necessary because the Gavrilović model considers total sediment load, whereas the conducted measurements only considered suspended load. Other verification methods encompassed the use of a PDA device and on-site observations (Tosic et al., 2012), and certain verification methods remain unspecified in the paper (Abadi and Ahmadi, 2011, Ghobadi et al., 2011) but provide poor overall ratings for the Gavrilović method by overestimating the sediment yield (Abadi and Ahmadi, 2011).

5.9 Conclusion and guidelines for further research based on the Erosion Potential (Gavrilović) Method application

In this chapter a detailed review of the application of the Gavrilović method was presented. The Gavrilović model is a semi-quantitative model that enables assessments of erosion severity, total annual sediment production and actual sediment yield involved in transportation. The most commonly calculated results using the model are the Total annual volume of the soil and the erosion coefficient. The actual sediment yield has been calculated for only 38% of the catchments. Although several modifications of the model have been used over the years, different variations of the model continue to be applied. These variations concern the assessment of the actual sediment yield involved in transportation. The analyses have obtained better results and correspondence with on-site measurements when a modified formula for the sediment delivery ratio that includes the drainage density as the ratio between the primary and secondary river length and catchment area is used. If the simplified (original) formula is used and the ratio is replaced with a constant, the values obtained using the model can exceed the predicted values for the total annual volume of the soil or the overall yearly amount of detached soil. Therefore, it can be concluded that the use of the formula for the drainage density is recommended for all future analyses to avoid incorrect results indicating larger values for the actual sediment yield compared to those of the total annual volume of the soil. However, none of the analysed papers include an explanation as to why a given formula, original or modified, was used over the other. Additionally, these papers did not provide a comparison that could roughly estimate the error/difference between the calculated and measured values if both formulas were used.

It was previously mentioned that the evolution of the Gavrilović model began with the development of GIS technologies. Until today, this method had not yet explored all the possibilities of GIS. For example, the actual sediment yield or sediment involved in transportation is calculated within the method for the entire catchment/sub-catchment and refers to the value representing sediment transportation, measured at the tow of the catchment. Today, GIS technologies enable the assessment of each cell within the catchment and as such can provide an estimation of the transported material in each cell representing the river. This approach can to some extent simplify the process of choosing the best location for field measurements in less accessible catchments as well as provide multiple options as adequate positions for field measurements. Thus, the verification of the method in terms of the assessed parameter for actual sediment yield can also be simplified and conducted on any part/length of the river, which can potentially lead to more frequent calculations of this parameter. To achieve this, the analysis must be narrowed down from the catchment and sub-catchment assessment at the cell resolution and later gradually broadened to the catchment size. Unfortunately, this procedure will continue to depend upon the resolution of available input data.

Lazarević, Globevnik, Fanetti and Vezzoli significantly improved the method using changes in the assessment of descriptive parameters within the model. It is important to note that certain catchment areas are currently affected by substantial changes in type, extent and density of vegetation cover as well as the expansion of urban areas. Therefore, if this is considered, the land use/cover parameter represents an extremely important parameter and will affect the final estimated values, as shown in the various previously mentioned papers (Solaimani et al., 2009a and b; Solaimani and Modallaldoust, 2008; Tangestani, 2006; Deilami et al., 2012; Kouhpeima et al., 2011; Ghazavi, et al., 2012, Barmaki et al., 2012a and b).

For such areas of intensive urban changes following the assessment of soil protection, the parameter for urban areas (Table 12) is recommended for future analysis. It is often forgotten in erosion analysis that agricultural areas and areas with low or no vegetation cover are not the only source of eroded material in a certain catchment. Therefore, all catchments are unique and complex in their own way, and additional sources of erosion material should be considered. The first and most important sources are construction areas in regions of urban expansion. These areas, although short lived, have a substantial impact on the amount of erosion sediment production on a yearly basis and should be considered when planning future activities in the catchment. Another source of erosion material that is rarely considered are residential areas with small green plots used mainly for agriculture. In larger towns, such areas are not considered to be significant; however, in suburbs, smaller towns and villages where such residential areas are often represented, this can be considered to be a problem and an additional source of erosion material that is often forgotten and simply classified as urban/rural area. Therefore, Table 15 suggests a new categorisation for the Soil protection coefficient for urban/rural areas, including undeveloped areas designated for urban development in the near future. Such a categorisation would change the model output information concerning erosion intensity and total amount of erosion material.

Table 15: Proposed assessment of soil protection coefficient for urban areas

Proposed descriptive evaluation of Soil protection coefficient for urban/rural areas [X_a]	**Proposed numeric evaluation**
Dense urban area with no or little green area	0.05
Scattered urban/rural residential area with green plots used mainly for agriculture	0.3
Construction area	0.9

Land use/cover parameters have exhibited a significant influence on the final results of the model and have led to predictions of decreased erosion production if appropriate land use management is applied. Dragičević et al. (2014a) highlighted the problem by obtaining different results by simply using a different land use/cover input source. Therefore, it can be concluded that the reliability of the final results is strongly correlated with the data source, experience of the expert in charge of map production, as well as the accuracy and level of detail of input data. The expert conducting the erosion analysis should also consider different data sets/maps available for the same parameter, compare their differences and, based on field surveys and local population information exchange, choose the best option for future analysis, as shown in (Zorn and Komac, 2009; Zorn et al., 2007; Dragičević et al., 2014a).

Note that the verification aspect of the analysis is omitted in most of the analysed papers, which leads to a shortage of information concerning the adaptability and applicability of the Gavrilović method to different areas varying primarily in terms of geology and hydrology. The lack of these data has also provided fewer opportunities to examine the possibilities of method modification because these data have yet to be provided. Additionally, several papers note the strong correlation between the knowledge and experience of the erosion expert and the deviation of predicted and measured sediment yield. Not one of the papers containing verification addresses the sensitivity of the model and uncertainty of the overall results regarding the source of the input data. Such analysis will be addressed in the next chapter of the thesis. The verification of the models should be conducted with greater frequency to obtain a better correspondence between on-site measured values for sediment production and those obtained with the model.

CHAPTER 6: METHOD PARAMETER DESCRIPTION AND DATA AVAILABILITY

For the purposes of this analysis, detailed and comprehensive data collection for the Dubračina catchment was conducted using sources from a variety of academic, governmental and non-governmental institutions. For each parameter several different input maps were derived depending on the needed time series for which the model output was calculated. Those time series can be divided into average annual past and present time as well as average seasonal (winter, spring, summer and autumn) time series for the present time (Figure 14).

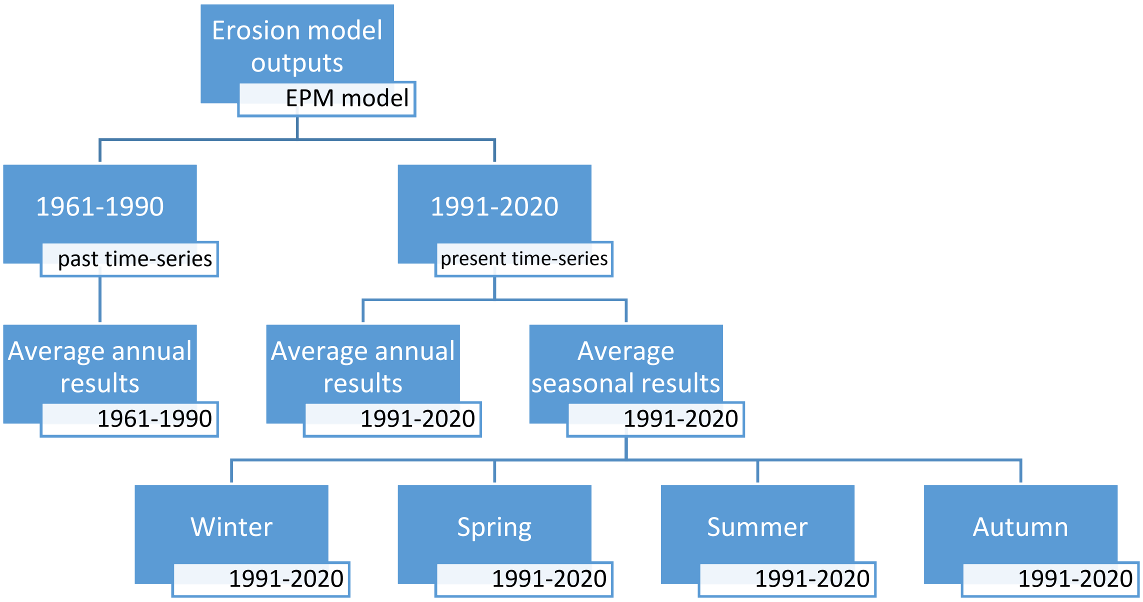


Figure 14: Time series used as past and present periods for which the erosion model outputs were derived

The necessary data can be subdivided into spatially variant input parameters (precipitation, temperature and land cover/use, soil erodibility, average slope of the study area, coefficient of type and extent of erosion and mean difference in elevation of the study area) and spatially invariant parameters (study area, perimeter of the watershed, length of the principal waterways and cumulated length of the principal and the secondary waterways). Each of this parameters will be briefly explained within this chapter.

6.1 Spatially variant parameters

6.1.1 Temperature and precipitation parameters

The importance and the role of temperature and precipitation in erosion processes has been the topic of many studies since the beginning of scientific interest in erosion processes. Their effect and relation to erosion processes has been described in detail by various authors (Morgan, 2005; Scholz et al., 2007; Assouline and Ben-Hur, 2006; Römkens et al., 2001; Toy et al., 2002; Blanco and Lal, 2008) and mentioned briefly in the Chapter 2 of this thesis.

6.1.1.1 Average annual temperature and precipitation

The spatial distributions for average annual precipitation P_a and temperature T_0, with a resolution of 1000x1000 m, were obtained from the Croatian Meteorological and Hydrological Service for the time period of 1961 to 1990, representing past. In addition to that, the Croatian Meteorological and Hydrological Service has provided the average monthly and annual precipitation and temperature for the meteorological station Crikvenica for the time period from 1961 to the end of 2014. In order to derive model outputs representing the present, the precipitation and temperature representing present time (1991 - 2020) were needed. Both the difference in mean values (Table 16) between the two time periods (1961-1990 and 1991-2014) and trends encompassing the time range from 1961 to 2014 (Figure 15) indicate the increase in values for both parameters.

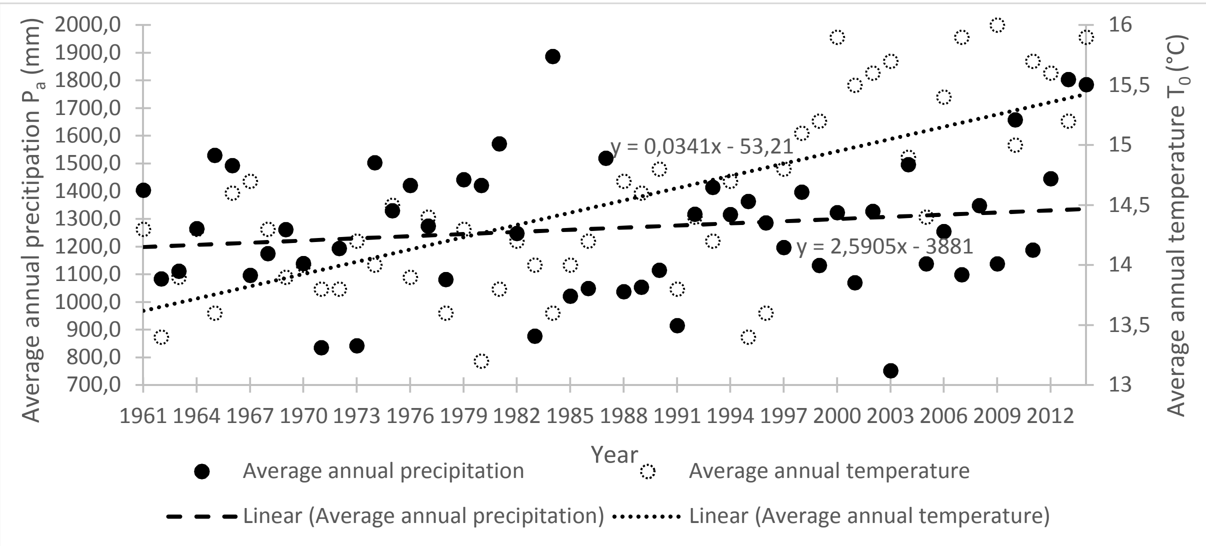


Figure 15: Average annual temperature and precipitation at the Crikvenica meteorological station from 1961 to 2014 and corresponding trends

Table 16: Average annual temperature and precipitation for Crikvenica meteorological station from 1961 to 2014 year (based on data obtained from Croatian Meteorological and Hydrological Service)

Year (1961-1990)	Average annual temperature T_0[°C]	Average annual precipitation P_a[mm]	Year (1991-2014)	Average annual temperatur e T_0 [°C]	Average annual precipitation P_a[mm]
1961	14,3	1403,6	1991	13,8	914,7
1962	13,4	1083,9	1992	14,4	1316,8
1963	13,9	1111,5	1993	14,2	1414
1964	14,3	1264,9	1994	14,7	1315,8
1965	13,6	1529,9	1995	13,4	1363,6
1966	14,6	1492,7	1996	13,6	1286,1
1967	14,7	1096,4	1997	14,8	1197,4
1968	14,3	1174,7	1998	15,1	1397,5
1969	13,9	1262,0	1999	15,2	1132,5
1970	14	1139,1	2000	15,9	1322,8
1971	13,8	835,0	2001	15,5	1070,3
1972	13,8	1193,2	2002	15,6	1328,1
1973	14,2	842,2	2003	15,7	752,4
1974	14	1503,1	2004	14,9	1496,5
1975	14,5	1330,1	2005	14,4	1137,9
1976	13,9	1421,3	2006	15,4	1255,5
1977	14,4	1274,8	2007	15,9	1098,5
1978	13,6	1081,2	2008		1348,7
1979	14,3	1441,8	2009	16	1138,1
1980	13,2	1421,3	2010	15	1658,0
1981	13,8	1572,0	2011	15,7	1187,6
1982	14,2	1248,2	2012	15,6	1445,2
1983	14	877,0	2013	15,2	1803,9
1984	13,6	1887,2	2014	15,9	1785,8
1985	14	1021,5			
1986	14,2	1049,3			
1987		1519,1			
1988	14,7	1037,7			
1989	14,6	1054,0			
1990	14,8	1115,5			
Average $T_{0(1961-1990)}$	14.1		Average $T_{0(1991-2014)}$	15.0	
	Average $P_{a(1961-1990)}$	1242.8		Average $P_{a(1991-2014)}$	1298.7
$T_{0(1961-1990)-(1991-2020)}$		+0.9°C	$P_{a(1961-1990)-(1991-2020)}$		+55.9

The statistical analysis, T-test with 95% of confidence (two-tailed test), was conducted with a purpose to define if the difference within the mean values between the two time periods, for both temperature and precipitation, is significant. The null hypothesis assumes that the two data sets are likely to have come from distributions with equal population means. For the temperature parameter, where p-value ($9.21*10^{-8}$) < α (0.05), the analysis has confirmed a significant change in temperature mean values for the two time periods, which was not the case with the precipitation, where p-value (0.249) > α (0.05). Based on twenty-four year changes in rainfall and temperature for the town of Crikvenica (Table 15 and Figure 16) and on the assumption that the spatial distribution pattern remains the same throughout the catchment, the spatial distribution maps for these parameters were derived for the present time (1991-2020) by adding the calculated change to each cell value.

Note that both the average annual temperature T_0 and the average annual precipitation P_a for the town of Crikvenica were found to increase for the period from 1991 to today compared to the period of 1961 to 1990 (by 0.9°C and 55.9 mm). The difference in the input data sets for temperature and precipitation are based on these changes.

6.1.1.2 Average seasonal temperature and precipitation

Spatial distribution maps representing Average seasonal temperature and precipitation at the Dubračina catchment were obtained from the Croatian Meteorological and Hydrological Service for the past time period (1961-1990). The maps representing seasonal values for temperature are actually maps representing average temperature for January (winter), April (spring), July (summer) and October (autumn). However, that is not the case with maps representing average seasonal precipitation where the values represent the three month average for each season. The maps representing average seasonal temperature and precipitation for the present time (1991-2020) are obtained by adding/subtracting the difference (Table 17) obtained from the analysis of Crikvenica meteorological station in the same way as for the maps representing annual values.

Comparing the two time periods, it can be seen that average seasonal temperature raises in every season from winter to autumn, with the highest recorded increase in summer period (+1.6°C). Both winter and autumn show the increase by +0.9°C between the past and present time periods. The pattern indicating the change in average seasonal precipitation differs from the one obtained for temperature. The average seasonal precipitation rises in winter where the small changes in average values are noted (+17.4 mm), and autumn, where the highest seasonal increase is recorded (+83.2 mm). The decrease in average precipitation is present for two other seasons, spring and summer, with the smallest changes recorded (-10.4 mm) for summer period and higher (-34.3 mm) for spring season.

Table 17: Average seasonal temperature and precipitation based on Crikvenica meteorological station (based on data obtained from Croatian Meteorological and Hydrological Service)

Average seasonal temperature T_0 [°C]/ Time series	**January (Winter)**	**April (Spring)**	**July (Summer)**	**October (Autumn)**
1961-1990	5.8	12.4	23.3	15.1
1991-2020	6.7	13.5	24.9	16.0
ΔT_0	+0.9	+1.1	+1.6	+0.9
Average seasonal precipitation P_a [mm]/ Time series	**Winter**	**Spring**	**Summer**	**Autumn**
1961-1990	287.6	283.7	237.5	434.1
1991-2020	305.0	249.4	227.0	517.3
ΔP_a	+17.4	-34.3	-10.4	+83.2

It should be noted that average annual precipitation shows the overall increase in its value, while on the seasonal level two out of four seasons shown increase in its values. That is not the case with temperature, where both average annual temperature and all seasonal temperatures show the increase in their values between the two time series (past and present). The increase in temperatures and increase/decrease in precipitation between the two time periods indicate climate changes. The statistical analysis, T-test with 95% of confidence (two-tailed test), was conducted with the assumption of the null hypothesis that the two data sets are likely to have come from distributions with equal population means. The analysis has confirmed a significant change in seasonal temperatures mean values between the two time periods (past and present), where p-values for the winter is 0.037, for the spring 0.007, for the summer 1.21×10^{-9} and for the autumn 0.019, all of which are less than α (0.05). The change in seasonal precipitation mean values was not found significant, with p-values for winter 0.58; spring 0.176, summer 0.70 and autumn 0.115, all with higher values then α (0.05).

6.1.2 Soil erodibility coefficient

Soil erodibility is one of the most important parameters integrated in erosion models. Its significance has been pointed by many scientists before such as Morgan (2005), Bryan (1968 and 2000), Le Hir et al. (2007) and Wischmeier and Mannering (1969).

Soil erodibility coefficient is based on soil type on Dubračina catchment. For the purpose of uncertainty analysis, described later in the chapter 8, two different soil erodibility maps were derived. First is based on Geological map of Dubračina catchment with the scale 1:25 000 (Figure 16 and Table 18) and evaluated according to the proposed tables for the Gavrilović method (Table 8 and 12) in the Chapter 5. The second variant of Soil erodibility coefficient used in the analysis shown in this thesis is based on Pedological map of Primorsko-goranska county with a scale 1: 100 000 (Figure 17). The evaluation of the soil erodibility coefficient based on Pedology map (Table 19) was made according to the nomographs used for the evaluation of soil erodibility in Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) (Figure 18).

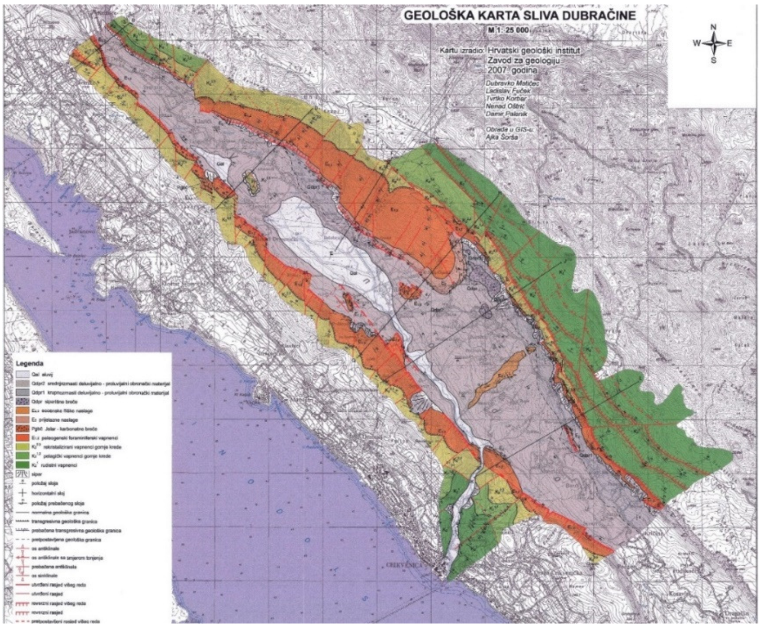


Figure 16: Soil type categories for Dubračina catchment based on Pedology map of Primorsko-Goranska County

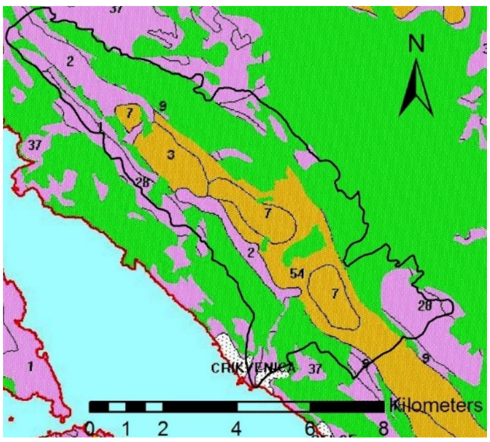


Figure 17: Dubračina catchment geological map (Geološko-tektonska osnova za studij pojačane erozije u slivu Dubračine, 2007)

Table 18: Categorisation and evaluation off soil erodibility coefficient based on geology map and its stratigraphical units

Symbol	**Stratigraphical units**	**Soil erodibility coefficient Y**
Q_{al}	Fluvial deposits, Quaternary	1.0
Q_{dpr2}	Slope deposits, Quaternary, coarse-grained to Fine-Grained Soils	1.0
Q_{dpr1}	Slope deposits, Quaternary, Coarse-Grained soils	1.0
Q_{dpr}	Slope deposits, Quaternary	0.9
$E_{2,3}$	Flysch deposits, Paleocene	1.1
E_2	Transitional deposits, Paleogene	0.9
$P_{gbč}$	Carbonate breccia	0.25
$E_{1,2}$	Foraminiferal limestones, Paleogene	0.4
$K_2^{2,3}$	Limestones, Creaceous	0.25
$K_2^{1,2}$	Limestones, Creaceous	0.25
K_2^1	Limestones, Creaceous	0.25
	Talus	0.9

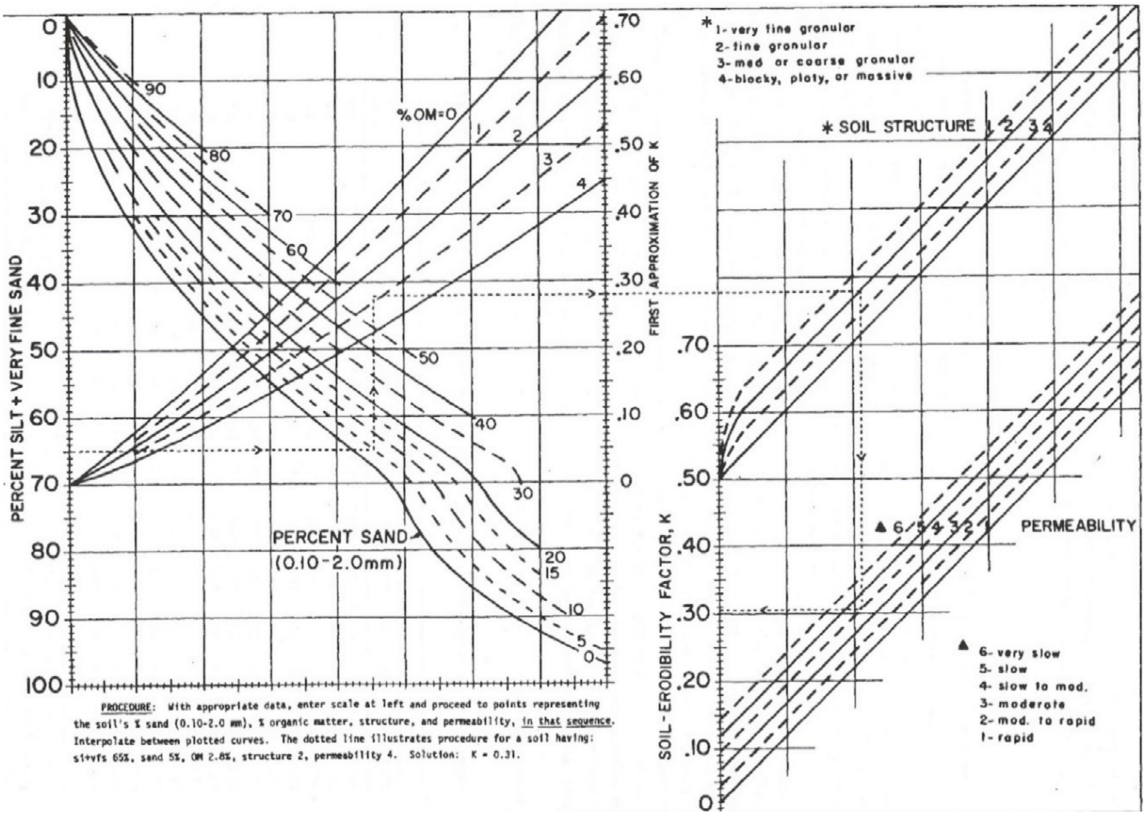


Figure 18: The soil erodibility nomograph used in USLE method (Wischmeier and Smith, 1978)

The nomographs are used for the soils where the silt fraction does not exceed 70% and are used to solve the equation 8:

$$100K = 2.1M^{1.14}(10^{-4})(12 - a) + 3.25(b - 2) + 2.5(c - 3) \quad (8)$$

Where:

K – soil erodibility coefficient
M – the particle size parameter
a – percent of organic matter
b – the soil structure code used in soil classification
c – the profile permeability class

Soil erodibility coefficient based on pedological map is chosen as soil type primary information source used in the Gavrilović model and analysis presented in this theses. The soil type categories defined within the pedological map provide more detail about soil characteristics in the catchment needed for the determination of the soil erodibility coefficient than those provided with the geology map. The evaluation procedure for the Soil erodibility coefficient using the nomographs from the USLE method has been verified and used numerous times in various methods (USLE, RUSLE, WEPP, etc..). This methodology was found to be more appropriate than the proposed descriptive and numerical evaluation used in Gavrilović method because it provides more quantitative approach to its evaluation and considerers soil characteristics such as percentage of organic meter, particle size, soil structure and permeability while the tables provided with the Gavrilović method provide more descriptive evaluation of soil type. Since, for the both evaluation processes the soil erodibility coefficient value range is from zero (0) to one (1), the USLE approach is considered to be applicable and appropriate amendment to the Gavilović method.

Table 19: Categorisation and evaluation off soil erodibility coefficient based on geology map

Soil type No.	Soil type: name and structure	Soil erodibility coefficient for each soil type	Percentage of soil type in each soil category [%]	Corrected Soil erodibility coefficient Y	Soil erodibility coefficient Y
1	Lithosol on Limestone and Dolomite	0.6	50	*0.3*	0.565
	Rendzina on Limestone and Dolomite	0.6	20	0.12	
	Kalkomelanosol	0.7	20	0.14	
	Kalkocambisol	0.5	10	0.005	
2	Colluvial soil Calcareous and/or Eutric	0.85	60	0.51	0.748
	Rendzina on Colluvium	0.61	30	0.183	
	Kalkocambisol	0.55	10	0.055	
3	Alluvial- Colluvial soil	0.40	80	0.3	0.428
	Hypogley	0.72	10	0.072	
	Calcareous	0.36	10	0.036	
7	Rendzina on marl Limestone	0.82	50	0.41	0.732
	Rigosol	0.54	30	0.162	
	Regosols	0.80	20	0.166	
9	Rendzina on Talus	0.78	60	0.468	0.7
	Colluvial soil	0.54	20	0.108	
	Kalkocambisol, Colluvial	0.62	20	0.124	
28	Kalkocambisol	0.42	50	0.21	0.478
	Rendzina on Dolomite Moderately deep and Shallow	0.60	30	0.18	
	Luvisol	0.44	29	0.088	
35	Kalkocambisol	0.44	60	0.264	0.544
	Kalkomelanosol	0.78	30	0.234	
	Luvisol on Limestone and Dolomite	0.46	10	0.046	
37	Kalkocambisol	0.44	50	0.22	0.5
	Terra rossa Typical, Luvic	0.36	30	0.108	
	Kalkomelanosol	0.86	20	0.172	
54	Rigosol on Colluvium and Flysch	0.82	60	0.492	0.722
	Colluvial soil Calcareous	0.54	30	0.162	
	Rendzina on Colluvium, Flysch and Talus	0.68	10	0.068	
58	Urban area	0.1	100	0.1	0.1

Tr4In Figure 19 can be seen that both soil erodibility coefficients differ spatially in their values as well as in their value range.

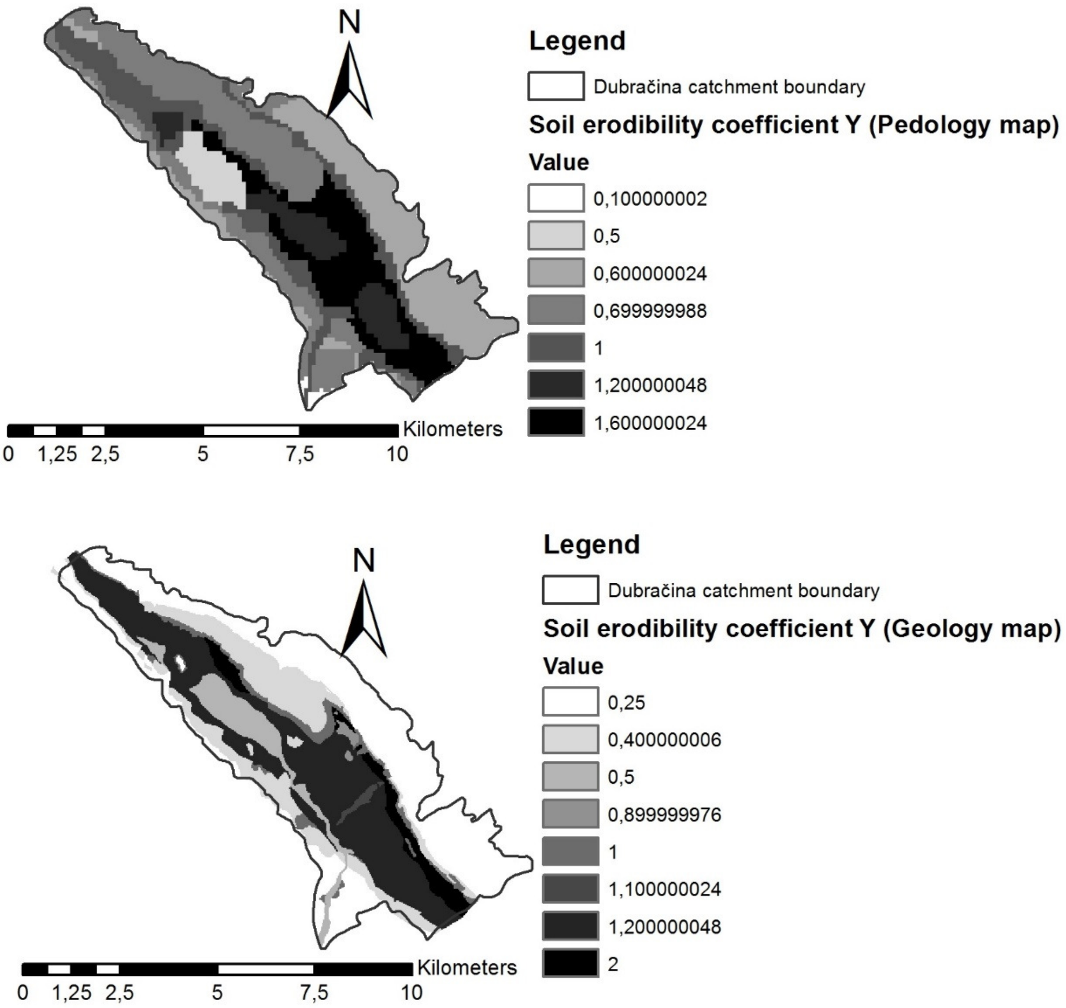


Figure 19: The soil erodibility coefficient based on different data source

6.1.3 Soil protection coefficient

6.1.3.1 Land cover/use data sources used for the derivation of soil protection coefficient for past and present time series

Two different land cover/use data sets were initially available; the 1:100,000 scale CORINE land cover map produced by the European Commission (EC) in 2006 and the 1:25,000 Spatial Plan of land use produced by the Croatian Government in 2004. The CORINE data were available at a spatial resolution of 100x100 m whilst the Spatial Plan was converted to raster format at a spatial resolution of 25x25 m. A third data set, based on supervised classification of a recent (August, 2013) Landsat 8 scene was subsequently included in the study to provide a more up-to-date and higher resolution (15x15m) assessment of land cover than the CORINE data set. The land cover map based on Landsat scene was obtained using supervised classification of the data with the help of the ERDAS Imagine 2014 software. All the above mentioned land cover/use data sets are intended for the analysis of erosion sediment production for present time-series.

Table 20 summarizes the differences between the three land cover/use data sources in percentage terms for the following categories: water, agricultural areas, bare rock, bare soil to rare vegetation, rare to medium vegetation, dense vegetation, urban areas and exploitation of mineral resources (including cemeteries and construction sites).

In terms of attribution, the 'agricultural areas' land use category in the Spatial Plan is broadly equivalent to the 'bare soil to rare vegetation' land cover category in the CORINE and Landsat 8 data sets. The breakdown of land cover/use over the catchment is most similar between the Spatial Plan and Landsat 8 data sets for the categories 'bare soil to rare vegetation', 'agricultural areas' and 'urban areas'. The breakdown of land cover/use is most similar between the CORINE data and the Spatial Plan for the 'dense vegetation (forest)' category.

Table 20: Percentage breakdown of land cover/use for the Dubracina Catchment

Land Use/ Land Cover Category	**CORINE (100x100m)**	**Spatial Plan (25x25m)**	**Landsat 8 (15x15m)**
Water	1	1	1
Agricultural Areas		29	
Bare Rock	5		20
Bare Soil to Rare Vegetation	6		27
Rare to Medium Vegetation	24	8	31
Dense Vegetation (Forest)	52	54	13
Urban Areas	12	7	8
Exploitation of mineral resources		1	
Summary	**100**	**100**	**100**

As an input data for the soil protection coefficient for the analysis of erosion sediment production for the past time series Landsat 4, 5 scene was used dating from August 1984, with a resolution 30x30 m.

Land cover/use maps were evaluated by each land cover/use category in order to obtain Soil protection coefficient X_a map (Figure 20). The evaluation was conducted according to the proposed numerical evaluations given by Globevnik et al. (2003), Fanetti and Vezzoli (2007) and original author Gavrilović (1972), also described in the Chapter 5.

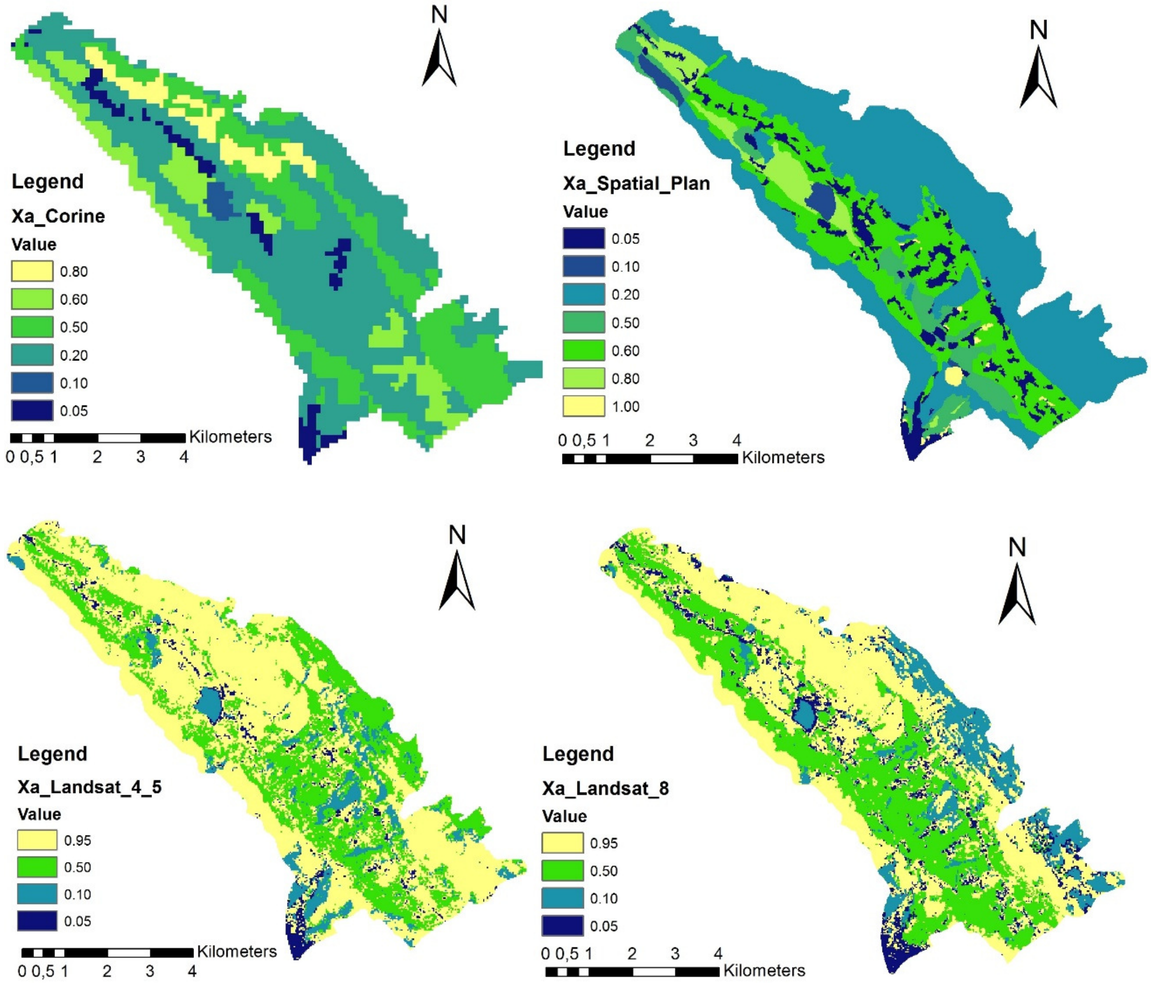


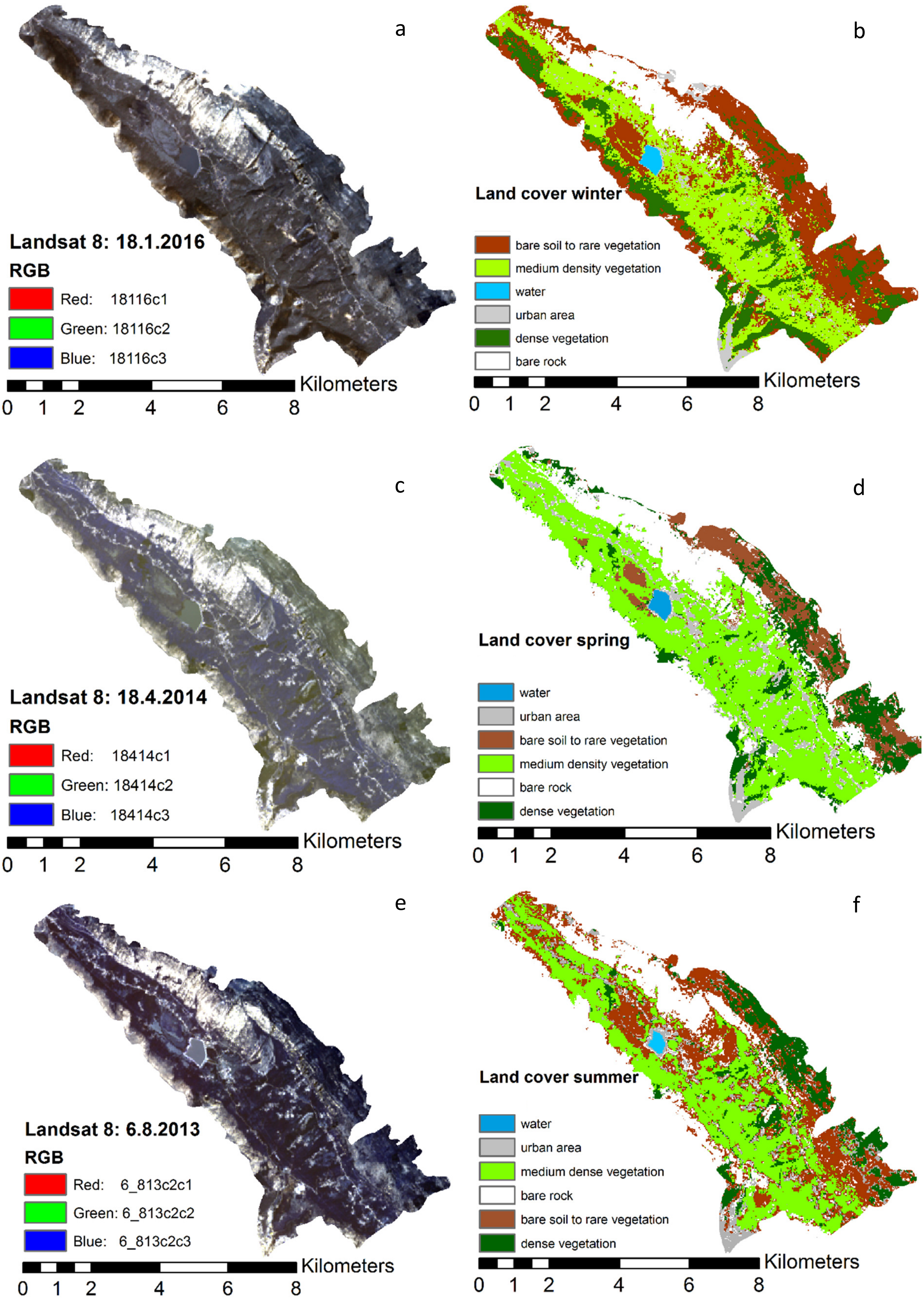
Figure 20: Soil protection coefficient according to numerical evaluation of different land cover/use maps

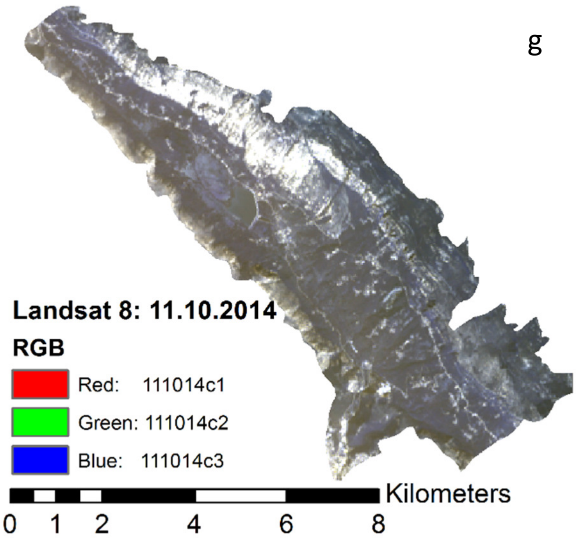
6.1.3.2 Seasonal soil protection coefficient based on Landsat 8 images

Four different Landsat 8 images, with resolution 15x15 m, were used for the derivation of seasonal land cover maps upon which soil protection coefficient is created. These images (Figure 21) date from:

- 18.1.2016 (winter time period)
- 18.4.2014 (spring time period)
- 6.8.2013 (summer time period)
- 11.10.2014 (autumn time period)

For the classification of these images ERDAS Imagine 2014 software was used to obtain land cover classes (Figure 21) and later ArcGIS 10.2 for the derivation of soil protection coefficient.


a
Landsat 8: 18.1.2016
RGB
Red: 18116c1
Green: 18116c2
Blue: 18116c3
Kilometers
0 1 2 4 6 8
b
Land cover winter
bare soil to rare vegetation
medium density vegetation
water
urban area
dense vegetation
bare rock
Kilometers
0 1 2 4 6 8
c
Landsat 8: 18.4.2014
RGB
Red: 18414c1
Green: 18414c2
Blue: 18414c3
Kilometers
0 1 2 4 6 8
d
Land cover spring
water
urban area
bare soil to rare vegetation
medium density vegetation
bare rock
dense vegetation
Kilometers
0 1 2 4 6 8
e
Landsat 8: 6.8.2013
RGB
Red: 6_813c2c1
Green: 6_813c2c2
Blue: 6_813c2c3
Kilometers
0 1 2 4 6 8
f
Land cover summer
water
urban area
medium dense vegetation
bare rock
bare soil to rare vegetation
dense vegetation
Kilometers
0 1 2 4 6 8



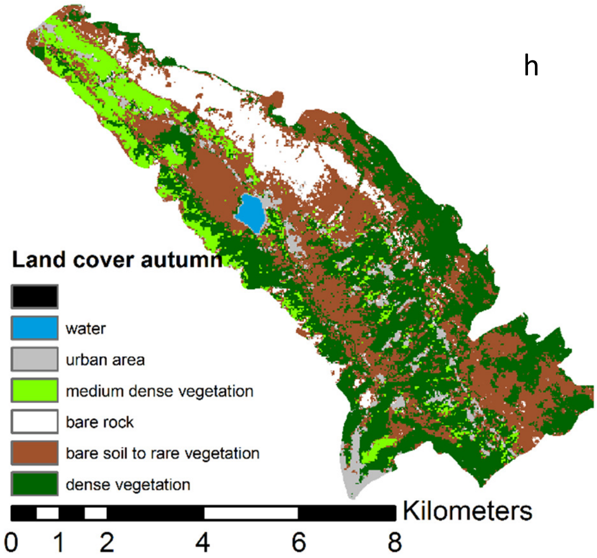


Figure 21: Landsat 8 images (a; c; e; g) used for the land cover classification on Dubračina catchment (b; d; f; h)

Images from different years were taken due to a large amount of noise on available images from Glovis USGS Landsat 8 archive. These images were selected so to have a good quality, low percentage of cloud cover, no missing data and to be closest in time to each other. The area coverage comparison between land cover categories is given in Figure 22. The biggest change is noticeable between dense, medium dense and bare soil to rare vegetation category. The changes in the urban area are related to the "errors" in misinterpreting urban area and bare rock categories shown and described later in Chapter 10. Bare rock is the most noticeable in spring and summer while in the autumn and winter it becomes bare soil to rare vegetation category. Bare soil to rare vegetation is the least widespread in the spring when the medium dense vegetation covers the largest area in the catchment. Dense vegetation is the most widespread in the autumn and decreases from winter to summer changing its category to medium dense vegetation.

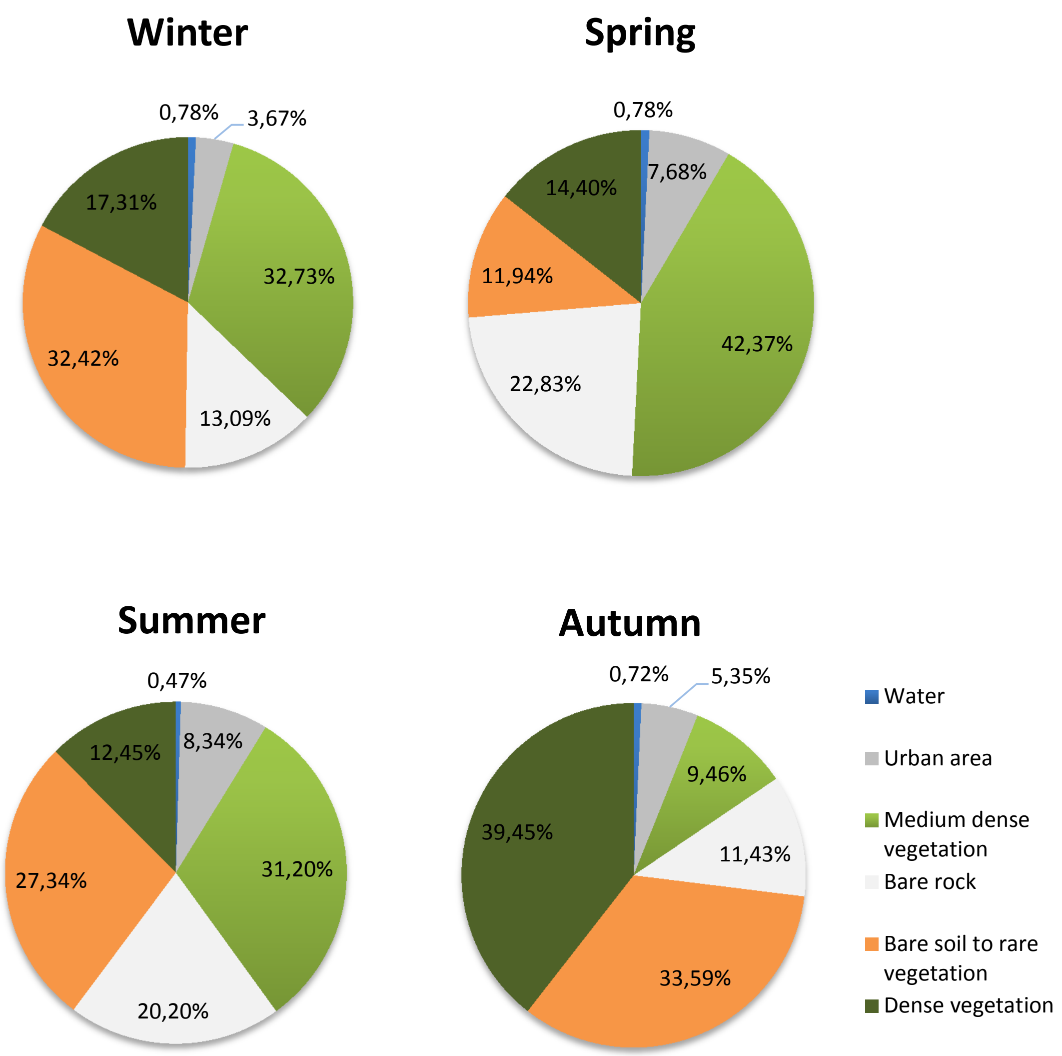


Figure 22: The percentage change in land cover categories throughout seasons

6.1.4 Coefficient of type and extent of erosion

The coefficient of type and extent of erosion was based on the Spatial Plan map of known erosion - affected areas (scale 1:25,000). The map of coefficient of type and extent of erosion has the resolution 25x25 m and has two values assigned (Figure 23). The value of 1 was assigned to all cells affected by erosion and the value 0.1 for the cell not affected by erosion according to the data source.

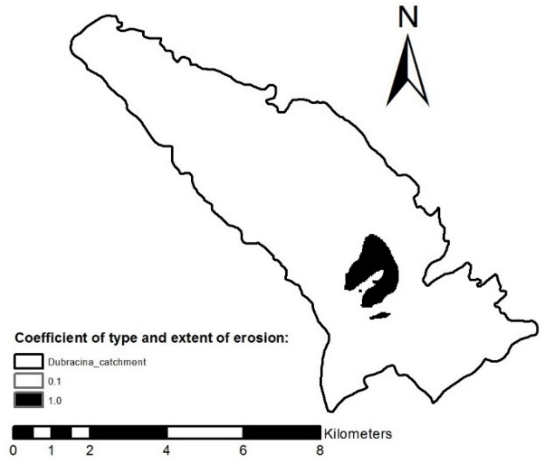


Figure 23: Numerical evaluation of Coefficient of type and extent of erosion based on Spatial Plan map of areas affected by erosion

6.1.5 Parameters generated from digital elevation model

LIDAR data were used to generate a digital elevation model with a 2x2-m cell size spatial resolution, from which the average slope of the study area map (Figure 24) and mean difference in elevation of the study area was derived.

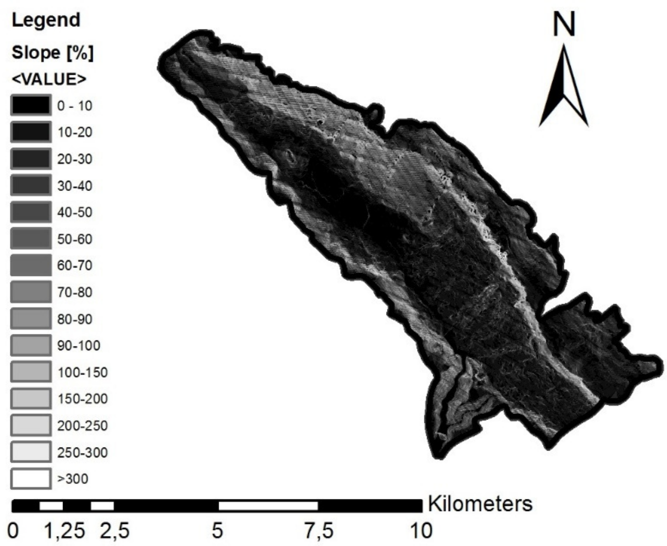


Figure 24: Average slope of the study area expressed in percentage

6.1.6 Drainage density

The drainage density map is based on river (primary and secondary) density calculated from the centre point of each map cell taking into account the values of all cells within the rectangle

1000 x 1000 m. The steps conducted to obtain drainage density map are discussed in more detail in Chapter 7.

6.2 Spatially invariant parameters

Spatially invariant parameters are those that are constant in their values for each cell size throughout the catchment area and include:

(i) Study area
(ii) Perimeter of the study area

all of which are considered basic catchment descriptors and used in the model as a constant values. The study area parameter doesn`t necessary represent the entire catchment area. Since the model is developed in ARCGIS software the study area used is actually defined cell size for the model output. Defined resolution, and in this case constant value for study area parameter, represented by a cell size is 100x100 m or 0.1 km^2. There was only one exception to that made when the calculation for drainage density map was produced. In its case the study area used was 1 km^2. The same principle was used for the calculation of a sediment delivery ratio where the value for the perimeter of the study area was taken as perimeter of a 1000x1000 m cell size or overall 4 km in length.

CHAPTER 7: DERIVING DRAINAGE DENSITY PARAMETER

The channel network is an idealized form in which the channels are represented by single lines and do not include lakes or confluences of more than two channels (Abrahams, 1984). According to Horton (1945) various aspects of drainage network forms can be quantified, such as stream order, bifurcation ratio, stream-length ratio, etc. In 1945, he proposed a several statistical laws, “Horton`s laws of drainage composition”, whose purpose was to characterize drainage basins. The one drainage basin attribute of the particular importance for this research that was proposed by Horton (1945), is drainage density. Drainage density, D_d (Equation 9) is defined as the total length of channels per unit area (Horton, 1945) and it describes the spacing and distribution of the drainage ways in a catchment (Glennon and Groves, 2002). It can be said that the ratio that defines drainage density also represents the amount of rivers in the catchment needed to drain the basin (Gallagher, 1999).

$$D_d = \frac{\sum_1^n L}{A} \tag{9}$$

Where:

L – Length of the waterway [km]
n – Number of waterways
A – Contributing drainage area [km^2]

When deriving drainage density for a catchment area, both perennial and intermittent rivers/tributaries need to be taken into consideration. If only perennial streams are included, drainage density value for the catchments with only intermittent streams would be equal to zero and in the flood event when both perennial and intermittent streams are active its values would be unrealistic (Horton, 1945).

According to Marani et al. (2003), drainage density, in practice, is defined by the statistical distribution and correlation structure of the lengths of un-channelled pathways (Marani et al., 2003). Drainage density is considered a useful measure of topographic texture of landforms in water eroded areas and often used to characterize landscapes (Abrahams, 1984). This parameter is not constant in time, it evolves trough time as the drainage system in a catchment evolves (Abrahams, 1984). This attribute of a drainage basin provides useful numerical measure of landscape dissection and runoff potential to hydrologists and geomorphologist. The higher values of the drainage density indicate lower infiltration rates and higher surface flow velocity (Yalcin, 2008). High drainage density is often related to high sediment yield transport trough river network, high flood peaks, steep hills, low suitability for agriculture.

To measure drainage density is extremely difficult and it relies on a good topographic maps in a detailed scale (Tucker, 2001; Dobos and Daroussin, 2005). As an alternative to drainage density, often a parameter potential drainage density is obtained from digital elevation data (DEM). The distinction between them is in the fact that the actual drainage density can be measured on site and it is based on the real drainage network map, while the potential one is derived from DEM and does not take into consideration the loss of surface runoff due to infiltration in the ground. For this reason, potential drainage density is always higher or equal to the actual drainage density in the analysed area (Dobos and Daroussin, 2005).

It can be said that the drainage density is inversely proportional to mean elevation and relief representing analysed area (Collins and Bras, 2010). Also, according to Glennon and Groves (2002), the inverse drainage density is the constant of channel maintenance or minimum area required for the development and maintenance of a unit length of channel. The average length of overland flow in most cases is approximately equal to half the average distance between the stream channels l_0 and approximately equal to half the reciprocal of drainage density (Equation 10):

$$l_0 = \frac{1}{2D_d} \tag{10}$$

According to Tucker et al. (2001) drainage density is physically related to the mean distance one has to walk from a random location before encountering a channel (Equation 10).

According to Gregory and Walling (2010) review research, drainage density is often used: (i) in relation to catchment characteristics such as soil type or shape of the catchment, (ii) as an input or output of the drainage basin system and (iii) in relation to past and future conditions. This parameter has been recognized as one of the most important characteristics of natural terrain and a frequent topic in hydrology and geomorphology till today.

7.1 Factors affecting drainage density and related research

Hydrogeological and geomorphological systems often have a heterogeneous characteristics that vary with scale from microstructures to continents (Luoto, 2007). Drainage network pattern is no exception, and consequently drainage density as well. The factors that influence drainage basin characteristics vary according to the scale of the input data (e.g. river network maps, digital elevation map,..). Abrahams (1984) analysed the scale dependence of the environmental factors and its influence on drainage density. He concluded that at the macroscale (between climate scale) the main influence on D_d has climate, where the most related parameter to D_d is mean annual precipitation. So, areas with arid climate (P_a<180mm) have low D_d. Their values reach its maximum in semiarid areas (180mm<P_a<380mm) and again decrease in humid areas (500mm<P_a<1000mm) and reaches it second maximum in super-humid areas (1500mm<P_a<3000mm). At the meso (within-climate) scale, D_d variations related to climate are small, but the variations regarding to lithology, relief or slope and the stage of drainage network development occur. At the micro (small-basin) scale even the length of streams in a single catchment or sub-catchment has an impact on D_d (Abrahams, 1984).

During the past several decades numerous quantitative studies have been conducted in order to define relationship between drainage density and its controlling factors such as climate, topography, soil infiltration capacity, vegetation and geology. Biswas et al. (1999) noticed that the low drainage density is associated to environmental characteristics incorporating permeable soil, dense vegetation and low relief, while high drainage density in areas with highly impermeable soils and high relief. Maximum runoff has been related to drainage density and according to Chorley and Morgan (1962) and Gregory and Walling (2010) reflects high intensity rainfall. Peek discharge (Benson, 1960), mean annual runoff, mean annual precipitation (Hadley and Schumm, 1961), average minimum monthly flow (Carlston, 1963), variations in sediment yield (Hadley and Schumm, 1961) have all been related to drainage density. According to Gregory and Walling (2010) research the relationship between drainage density and discharge Q can be expressed as (Equation 11):

$$Q \propto D_d^2 \tag{11}$$

Han et al. (2003) analysed relation between drainage density and active tectonics in Quaternary covered North China plain and concluded that the influence of non-tectonic factors on drainage is secondary but the correlation between the high-drainage density belts and the tectonics exists. Lin and Oguchi (2004) analysed the relationship between D_d and slope angle on the bare soils in Japan with the emphasis on channels with early stage of erosion. They concluded that although the slope angle or relief and D_d are positively correlated in some regions in the United States they are negatively correlated in the Japanese mountains.

Luoto (2007) preformed analysis on multiple spatial scales and two novel statistical methods (generalized linear modelling (GLM) and hierarchical partitioning (HP)) in subarctic Finland area in order to determine D_d controlling factors. He concluded that most of the variation in D_d are related to soil and vegetation properties of the analysed area, where D_d increases with higher proportion of rock and gravel soils and alpine vegetation and decreased with peat cover. They found topography and rock type to have less impact on D_d, which is opposite to high influence of the spatial scale. General conclusion is high importance of soil erodibility and relatively week effect of relief and bedrock geology on D_d.

The connection between the D_d and the flood statistics were investigated by Pallard et al. (2009). They concluded that D_d is higher in arid areas with sparse vegetation cover and has the tendency to increase with the increasing probability of heavy rainstorms. High values of D_d should be expected in highly branched drainage basins with rapid hydrological response. Overall, increasing drainage density implies increasing flood peaks and/or impervious soils, while decreasing D_d implies decreasing flood. Although, low D_d can be found in karstic area, highly weathered bedrock and/or highly permeable fluvial deposits in the valley floors, all of which points to large storage volumes and response times and consequently small flood peaks and volumes.

7.1.1 Drainage density in relation to soil erosion

During the last decades drainage density has been analysed in relation to many parameters among which soil erosion and soil erodibility (Collins and Bras, 2010) as well as sediment yield (Gregory and Walling, 2010). It is well known that bare soils are much more erodible or prone to soil erosion. Catchments with such characteristics have higher drainage density and higher runoff production which leads to large flood peaks and volume (Pallard et al., 2009). Luoto (2007) highlighted the importance of soil erodibility and its effect on D_d, and pointed relatively week effect of other parameters such as relief and bedrock geology on D_d in comparison. Also, catchments with higher drainage density are prone to higher sediment yield values (Hadley and Schumm (1961). According to Tucker and Bras (1998) a threshold for runoff erosion can influence landscape morphology and drainage density. Detachment-limited model was developed by Horward (1997) where the controlling factors defining the relationship between drainage density and mean erosion rate are the dominant hillslope transport process and the presence or absence of a threshold for runoff erosion. Relation between D_d and climatically driven erosional processes indicate D_d as a catchment characteristics that can give an insight to signature processes and landscape history in the catchment. Analysis comparing erosion rates and D_d can potentially be used to make conclusions about tectonic and geomorphic history (Tucker et al., 2001).

In 1945, Horton defined un-channelled slope as a "belt of no erosion" with insufficient overland flow strength to induce erosion. Later on, Montgomery and Dietrich (1989, 1992) as well as Dietrich et al. (1993) confirmed his hypothesis.

Negative correlation between D_d and slope angle are found in quickly eroding areas, while in areas prone to slow erosion processes the correlation between these two parameters is positive (Horward, 1997). The relationship between slope angle and D_d was found to be more directly related to the stages of channelization although previous research indicated its connection to dominant erosion types (Lin and Oguchi, 2004).

7.2 Different derivation methods for drainage density map

According to Gregory and Walling (2010) the usefulness of D_d as model input parameter is limited by the method used to derive the drainage network and the maps and its scales representing catchment river network.

Comparison of different techniques for derivation of drainage density have been given by Abrahams (1984) that singled out Carlston and Langbein (1960), McCoy (1971), Mark (1974) and Gardiner (1979) methods, and referring to Mark`s (1974) as the best among them for heaving a theoretical basis, universal applicability and no adjustable parameters.

The most often used way for presenting D_d (e.g. in Biswas et al., 1999; Yalcin, 2008; Çevik and Topal, 2003; etc.) is by using the single value for each sub-catchment calculated according to equation 9.

Four different ways to calculate D_d were considered by Beer and Borgas (1993) which included sub-catchment length-area relationship ($D_{d.1}$), the total length of stream as a function of scale ($D_{d.2}$), the mainstream length-area relationship ($D_{d.3}$) and the total area of stream as a function of areal scale ($D_{d.4}$).

The drainage density calculation for the Centa basin (Giannoni et al., 2005) incorporated both the area slope and the area filtering criteria that was specified to reproduce the D_d at the outlet.

Glennon and Groves (2002) applied five different techniques for the calculation of D_d taking into consideration examined area, surface stream length, the cave stream length and dye trace length in the karstic drainage basin.

The method based on measuring hillslope flow path distance at every un-channelled site within a catchment and analysing that field as a random space function was used for the calculation of D_d map by Tucker et al. (2001). They found a method to be consistent and efficient for the generation of D_d maps based on DEM and theoretically sound tool for estimating spatial variability of D_d. They applied the method to Reno catchment in the northern Apennines in Italy by first defining the local and easily measurable property, measuring the downslope distance to the nearest channel or valley form a given point and applying the random space function that averages hillslope flow path distance in space over a length scale equal to its autocorrelation scale, finally obtaining D_d map. They concluded that this method (the hillslope length method) provides a simple and straightforward way to analyse D_d both statisticaly considering its variation in values on an area of interest.

Vogt et al., (2003) used scoring system for the derivation of D_d and combined various environmental parameters such as precipitation effectiveness index, slope steepness, vegetation cover, rock erodibility and soil transmissivity. They concluded that such system provides a powerful technique for deriving homogeneous areas of D_d. After the area of interest is divided, each section is then assigned a value for each environmental parameter that was previously assigned with a weight value defined by its relation to D_d. Overall score is used as a representation of D_d and divided into five categories (very low, low, medium, high and very high). The purpose of such scoring system was not to derive actual values for D_d but to define areas with specific environmental conditions.

Richards (1979) proposed a number of alternative indices for D_d, that involve quadrat and line sampling methods and as such avoid the problems with catchment definition and irregular area measurements. They found that the method (the number of Shreve segments within a quadrat-sampling unit) can successfully be used to predict D_d.

Dobos and Daroussin (2005) derived potential drainage density map using ARCGIS surrounding's and the drainage network map derived from DEM (90 m resolution SRTM DEM). First to each cell representing drainage lines the value of one was assigned. Upon that, the drainage density map was derived as a function of sums of all cell values that fall within a predefined shaped and sized neighbourhood (circle). The value for each pixel was defined by moving the neighbourhood window and placing the desired pixel in the middle. Dobos and Daroussin (2005) suggested the size and shape of the neighbourhood window to be variable for different case studies, depending on the current situation and user`s need, with a respect to minimum needed window size in order to get at least one drainage cell to avoid having empty neighbourhoods and zero value of drainage density. Opposite to that, too large windows lead to generalizing the D_d map while smaller maintain the physiographic patterns.

Several authors proposed the categorisation for the D_d based on the definition of value range for each group/category. The values for D_d are subdivided into six groups by Han et al. (2003), where the numerical range for each group (Table 1) is not constant and its distribution is based on the area considerations where the higher values of D_d are covering smaller areas.

Table 21: Value ranges for drainage density within groups defined by Han et al. (2003)

Group:	1	2	3	4	5	6
D_d [km/km^2]	0-5	6-15	16-20	21-25	26-35	36-56

Ravi Shankar and Mohan (2006) divided the study area into cell size of one km^2, and the total length of all streams within the cell size was used to determine the drainage density. Obtained values were used as a background for D_d map and subdivided into four categories (Table 22).

Table 22: Categorisation of drainage density given by Ravi Shankar and Mohan (2006)

Category	Very low	Low	Medium	High
D_d [km/km^2]	<1.0	1.0-2.0	2.0-3.5	>3.5

There are many ways to derive D_d map, as shown by various researchers among which some are referred to in this chapter. The methodology chosen and used to derive D_d map for the Dubračina catchment area is shown in the next section of this chapter.

7.3 Deriving drainage density map for Dubračina catchment

Drainage density for Dubračina catchment was derived three times using different assumptions and allowing different spatial variability. For each case, drainage density was classified according to the proposed classification shown in Chapter 7.2 by Ravi Shankar and Mohan (2006).

In the first case drainage density for Dubračina catchment was derived with assumption that the entire catchment is homogeneous with no spatial variance in its characteristics and as such in D_d as well (Equation 3).

$$D_{d.Dubračina\ catchment} = \frac{l_a+l_p}{F} = \frac{40.227236}{43.54} = 0.9236\ km/km^2 \qquad (12)$$

The values obtained correspond to the very low drainage density class according to Ravi Shankar and Mohan (2006) D_d classification and are not spatially variable throughout the catchment.

The second case (Figure 25a) takes into consideration sub-catchments variability. In this case, D_d is calculated using the equation 9 for each sub-catchment separately. According to the Ravi Shankar and Mohan (2006) D_d classification five sub-catchments within the Dubračina catchment have very low D_d (Sušik, Kučina, Leskovnik, Ričina and Malenica), another six low D_d (Mužinići, Balasi, Mala Dubračina, Duboki, Slani Potok and Bronac) and only Bartolovac sub-catchments medium D_d. According to the previous research, referred in more detailed in earlier sections of this chapter, low values of drainage density can indicate different things from higher infiltration rates and lower surface flow velocity to lower values of sediment yield transport through river network all of which do not necessarily relate to Slani potok and Mala Dubračina sub-catchments. This method, as referred earlier, is the most often used for the calculation of D_d included in various erosion models. Both first and second case methodology for deriving D_d are continuously used in various case studies related to the application of the Gavrilović method.

For the third case (Figure 25b) the methodology proposed by Dobos and Daroussin (2005) with defined square shape neighbour window with a size 1x1 km for a cell size of 1x1m was used. The neighbour window with a size 1x1 km was chosen as to neutralize the value for area in the equation 9 and thus drainage density for each cell is equivalent to the summation of all primary and secondary river lengths within the square window of 1 km^2. For Dubračina catchment the actual drainage density is calculated, based on the river network map with a scale size 1:25 000, obtained from Spatial Plan of Vinodol Valley (2004), as opposite to the case presented by Dobos and Daroussin (2005) where potential drainage density was calculated based on DEM derived river network.

It can be seen from Figure 25 (a and b) and equation 12 the difference in spatial variability and value ranges for all three cases. Since, case 1 represents homogenous drainage density for the entire catchment and today technological possibilities provide much more detailed and accurate maps, this case is disregarded from the future analysis shown in this thesis. This map would in a need for an approximate and fast estimation of erosion sediment production, where most model parameters would be homogenous trough the catchment, be very useful and as such was applied many times on various catchment using Gavrilović method. Between the two other cases, case 3 provides the most spatially variant and is the most complex one to derive. Besides mentioned, case 3 D_d map provides most realistic spatial variance of the D_d parameter, with lower values of D_d along the edges of the catchment and higher values of D_d concentrated along the river and tributary intersections where higher surface velocity, less infiltration rates and higher values for sediment yield transport are expected.

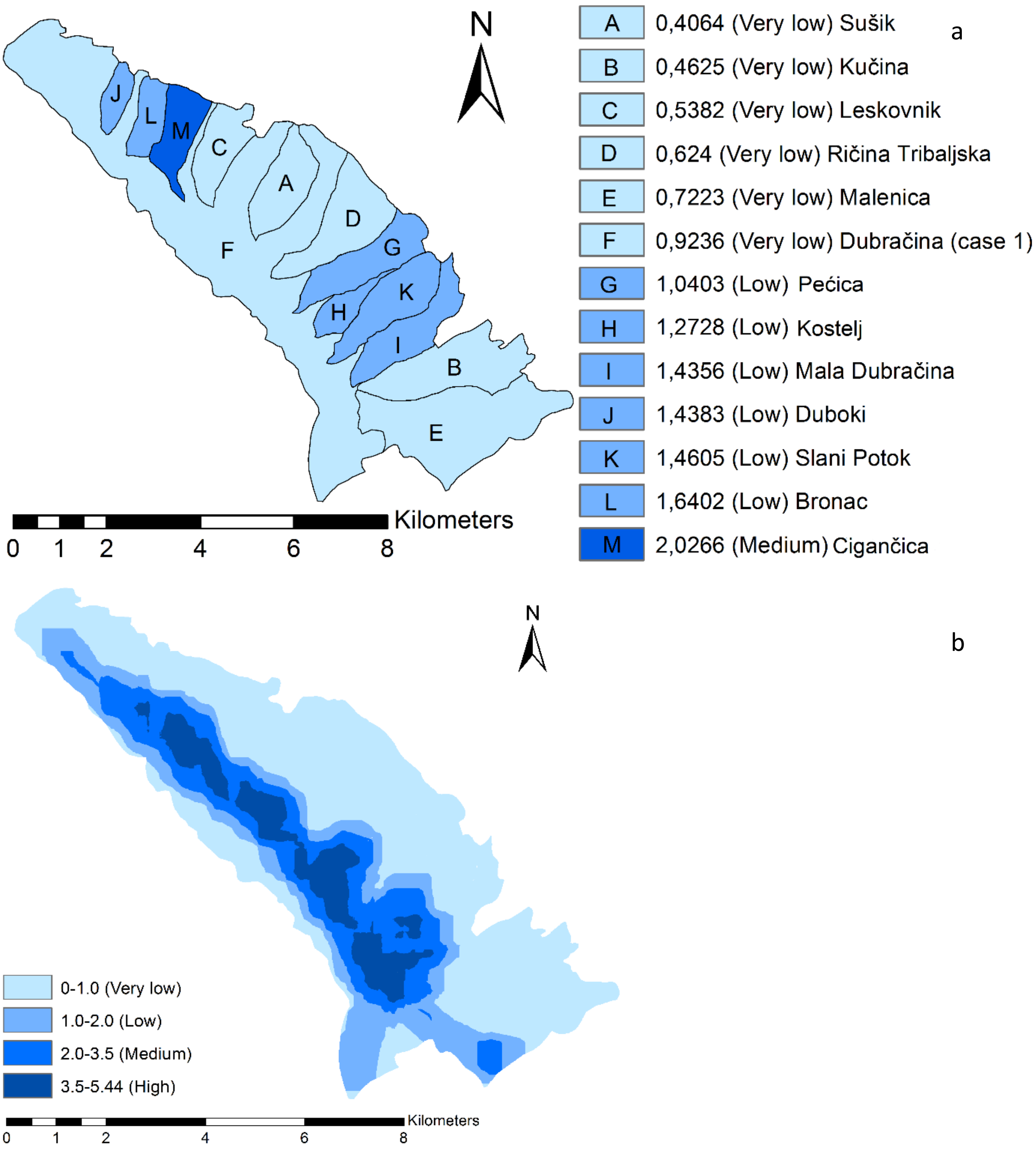


Figure 25: Drainage density for the Dubračina catchment: (a) Case 1: sub-catchment; (b) Case 2: spatial variability using Dobos and Daroussin (2005) methodology

The question is how do these three different drainage density derivation approaches affect the results of Gavrilović method? Since the main model parameter dependent upon drainage density parameter is Sediment delivery ratio ξ (Equation 4, Chapter 5), which is multiplied by the total annual volume of detached soil W_a in order to obtain actual sediment yield G_y, as shown in equation 7, chapter 5, the value range obtained for this parameter (Equation 13, Table 23 and Figure 26) using different drainage maps (case 1-3) is discussed.

$$\xi_{Case\ 1} = \frac{\sqrt{O*z}*(l_p+l_a)}{(l_p+10)*F} = 0.2445 \tag{13}$$

Table 23: Sediment delivery ratio for Case 2 – sub-catchment variation

Sub-catchment	**Sediment delivery ratio ξ**
Sušik	0.0853
Kučina	0.1126
Leskovnik	0.1112
Ričina Tribaljska	0.1379
Malenica	0.1649
Dubračina catchment (case 1)	0.2445
Pećica	0.2204
Kostelj	0.1903
Mala Dubračina	0.2886
Duboki	0.1909
Slani potok	0.2665
Bronac	0.2407
Cigančica	0.3291

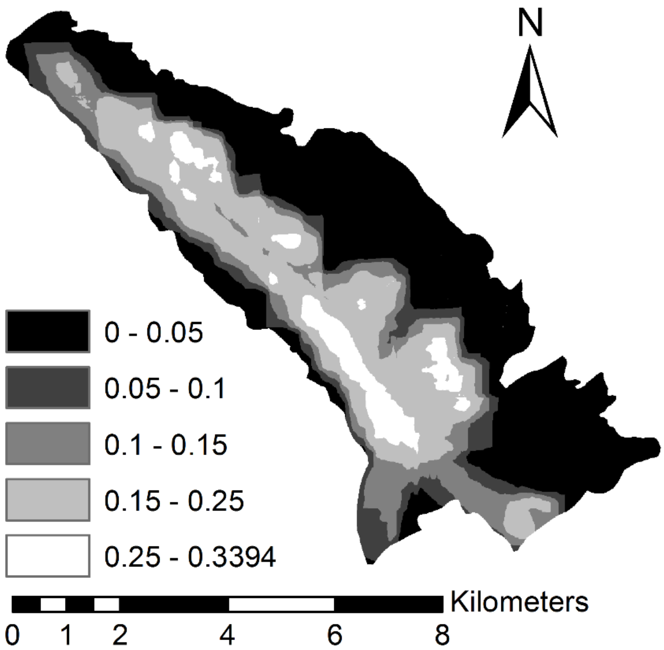


Figure 26: Sediment delivery ratio for the case 3

The values for sediment delivery ratio for the case 3 (Figure 26) range from 0.001 up to 0.3394. It can be concluded that the value ranges for case 2 and 3 do not differ significantly but the spatial variation of the parameter is significantly different and it follows the variation pattern the same as drainage density. Since, the case 3 provided the best spatial variability for drainage density parameter and its method was in previous research by Dobos and Daroussin (2005) approved and defined as appropriate method for drainage density map derivation, case 3 is chosen as the most appropriate for further analysis. Until today, to author of this thesis knowledge, there hasn`t been any research paper applying the Gavrilović method that uses this particular method for the derivation of drainage density and none to author of this thesis available and mentioned research papers in Chapter 5 use drainage density map with spatial variability that is more than on sub-catchment level. For this reason derived map for D_d using the case 3 methodology is considered an enhancement to Gavrilović method accuracy and precision.

CHAPTER 8: SOURCE- AND TIME-VARYING INPUT DATA IN CONTEXT OF EROSION POTENTIAL METHOD BASED MODEL UNCERTAINTY

The need for the information on soil erosion (Merritt et al., 2003), at temporal and spatial scales describing the sediment pattern throughout the catchment and its associated quantities, is increasing due to various demands from stakeholders and decision makers in spatial as well as soil and water conservation planning. In recent decades, many methods for erosion intensity and sediment production assessment have been developed. The necessity for better model performance has led to more frequent application of the method sensitivity and uncertainty assessments in order to decrease errors that arise from the model concept and its main assumptions (Merritt et al., 2003, Thiemann, 2006). According to Loucks and van Beck (2005) any model credibility relies on the accuracy and reliability of its outputs. Since, the availability of accurate input data is rare all models are inevitably imprecise. Repercussions of input data errors, as a result of inadequate information, incorrect assumptions, approximations in data measurement, or natural variability, is uncertainty in the model outcome (Loucks and van Beck, 2005; Jetten et al., 1999). Although, model uncertainty can be reduced to some degree, to eliminate it is almost impossible due to the existence of both known and unknown errors in the input data. This uncertainty is referred to as model parameter uncertainty. According to Jetten et al. (1999, 2003) the spatial and temporal variability of input data and uncertainty related to it is one of the main reasons erosion models deviate in their prediction capability.

There is a difference between model uncertainty and sensitivity analysis. While the uncertainty analysis attempts to identify magnitudes and conditions under which the model yields the highest uncertainties as well as average output uncertainty for a wide variety of modelling conditions (Chaves and Nearing, 1991), sensitivity analysis aims to determine the alteration of the model output as a function of the change in each one or in a set of input parameters (Loucks and van Beck, 2005; Morgan 2005) and quantitatively evaluates the influence of input parameters to model outcome (Thiemann, 2006). There are numerous studies (Frey, 1992; Torri et al, 1997; Quinton, 1997.; Brazier et al., 2000; Muleta and Nicklow, 2005; Li et al., 2007; Catari Yujra, 2010) that analysed different aspects of model uncertainty.

Today, numerous erosion assessment methods are being applied where each one has different constrains and capability to adjust to different environmental and on-site (e.g. administrative, data availability, financial…) conditions varying from case to case study.

Erosion model discussed within this chapter is based on the Erosion Potential (Gavrilović) Method and used to provide three main outputs (Figure 27): (i) the total annual volume of detached soil W_a, (ii) the erosion coefficient Z and (iii) the actual sediment yield G_y for the Dubračina catchment area.

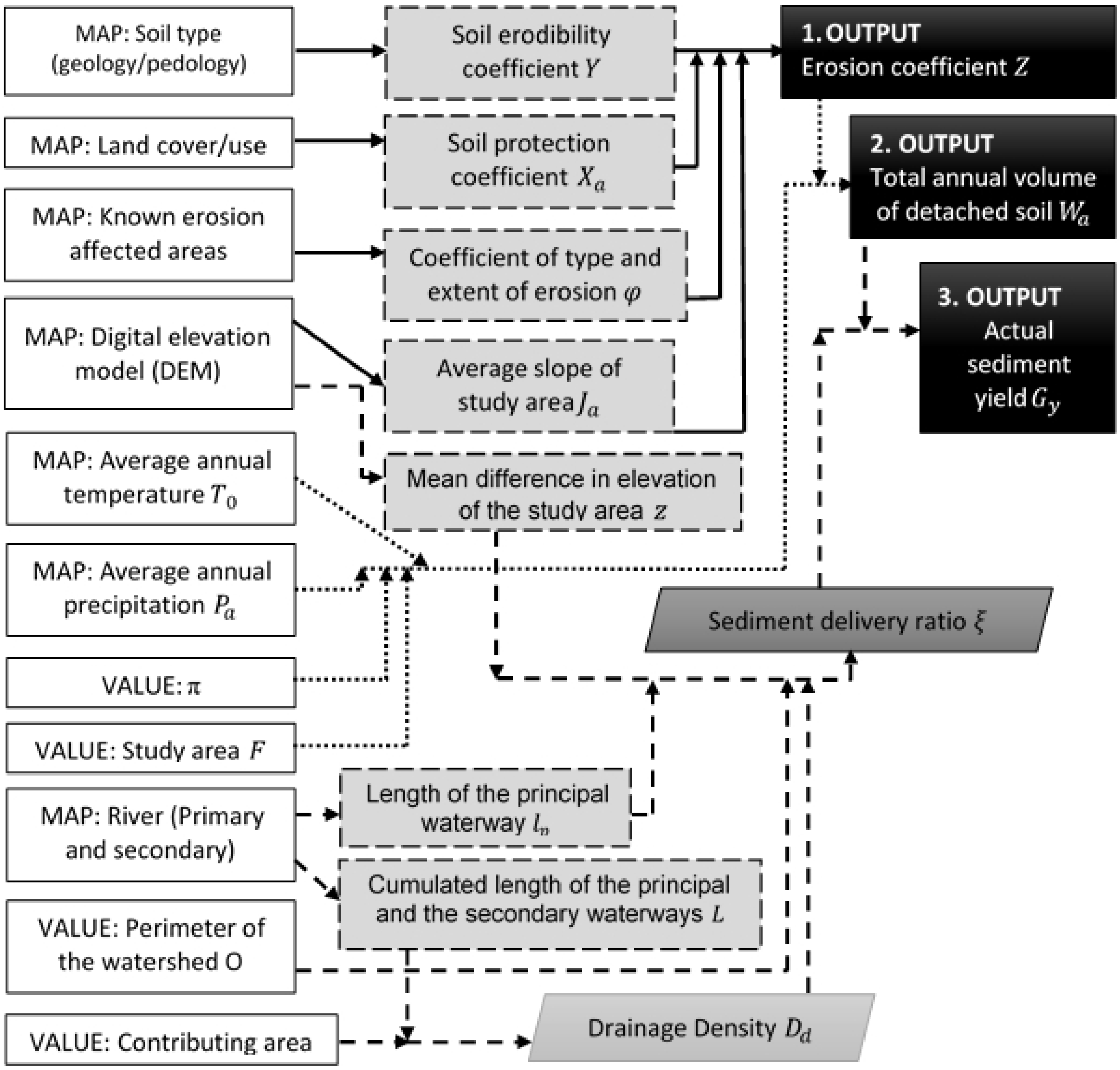


Figure 27: Flow chart of the model based on the Erosion Potential (Gavrilović) Method

There are numerous approaches to uncertainty analysis varying from analytical to numerical approaches. Some of them were described by Hammonds et al. (1994). For the purpose of this analysis numerical approach described in this chapter was used.

The objective of this research and model uncertainty analysis was to explore not only the constrains of the Gavrilović method but also drawbacks to the entire erosion evaluation process conducted, starting with data collection and data processing and leading to the final results. During the research, following questions were raised:

i. Which parameters yields higher uncertainty? Source or time-varying parameters?
ii. What parameter affects model uncertainty the most?
iii. To what extent can one parameter affect the prediction of the erosion model outputs if different data sources and sets are used?
iv. What could then be the criteria one expert should consider when gathering and choosing representative input data for his model?

This chapter attempts to provide the answers to the above questions. The analysis will address input data uncertainty through the analysis of the model parameters and model outputs for seven different scenarios. The purpose of this analysis was to indicate model uncertainty caused by the input data on model outcomes due to the change in source of information and the change in parameters over time.

8.1. Methodology and data

The data upon which uncertainty analysis is based can be subdivided into spatially variant data and time-variant data. The spatially variant data: (i) the soil protection coefficient based on land cover/use, and (ii) the soil erodibility coefficient based on soil type, both, vary depending on the source of the information. The time-variant data: (i) the average annual precipitation, (ii) the average annual temperature and (iii) the soil protection coefficient based on Landsat land cover scene differ with respect to the period for which model outputs are calculated. Within this analysis two time period were taken into account: (i) past 1961-1990 and (ii) present 1991-2020. All other data in this analysis, that are not subjected to change in data source or in time, are considered to be invariant.

For the uncertainty analysis the following input data (explained in detail in Chapter 6) were used:

(i) two data sets for Average annual precipitation P_a for different time periods (1961-1990 and 1991-2020)

(ii) two data sets for Average annual temperature T_0 also for the same time periods as (i),

(iii) Soil protection coefficient X_a based on four data sets representing land cover/use out of which three indicate change is source (Landsat 8, Corine and Spatial Plan) and two in time (Landsat 4,5 dating from the year 1984 and Landsat 8 dating from the year 2013) and

(iv) Soil erodibility coefficient Y represented by two data sets indicating soil type, one being Pedology and the other Geology map.

The uncertainty analysis in this chapter examines the model response to variations in time and source of information. Each one will be discussed separately. For this purpose, seven different model scenario were selected, each varying only one parameter in relation to scenario I, as seen in Table 24.

Table 24: Scenarios for uncertainty analysis and input data for spatially and time-varying parameters

Scenario	Average annual precipitation P_a	Average annual temperature T_0	Land cover/use data on which the Soil protection coefficient X_a is based	Soil type data on which the Soil erodibility coefficient Y is based
I	$P_{a(1991-2020)}$	$T_{0(1991-2020)}$	*Landsat 8*	*Pedology map*
II	$\boldsymbol{P_{a(1961-1990)}}$*	$T_{0(1991-2020)}$	*Landsat 8*	*Pedology map*
III	$P_{a(1991-2020)}$	$\boldsymbol{T_{0(1961-1990)}}$*	*Landsat 8*	*Pedology map*
IV	$P_{a(1991-2020)}$	$T_{0(1991-2020)}$	***Spatial Plan****	*Pedology map*
V	$P_{a(1991-2020)}$	$T_{0(1991-2020)}$	***Corine****	*Pedology map*
VI	$P_{a(1991-2020)}$	$T_{0(1991-2020)}$	***Landsat 4,5****	*Pedology map*
VII	$P_{a(1991-2020)}$	$T_{0(1991-2020)}$	*Landsat 8*	***Geology map****
***Changed parameter in relation to basic scenario I**				

The uncertainty analysis can be divided into three main elements. The first, indicating parameter uncertainty is based on a chosen sample size selected out of the population that encompasses all the cells in the Dubračina catchment. The second analyses method sensitivity to each parameter and provides information on which ranking of parameters can be made according to its contribution to model uncertainty. The third reflects overall uncertainty of a model output when the entire population is taken into account.

8.2 Uncertainty based on sample size

The sample size n was calculated (Equation 14-16) with the assumption that the margin of error allowed is five percent (5%), the confidence level is 95% and the population with a size N (4286 cells) is represented by the Total annual volume of detached soil W_a model output for scenario I.

$$n = \left(\frac{z\alpha/_2 * \sigma}{E}\right)^2 \quad (14)$$

$$f = \frac{n}{N} < 0.05 \quad (15)$$

If $f > 0.05$ then:

$$n' = \frac{n}{1+f} \quad (16)$$

Where:
n – Sample size
$z\alpha/_2$ - Confidence level
σ – Standard deviation
E – Margin of error
f - Sampling fraction
N – Population size
n' - Actual sample size

Calculated Actual sample size was 1005 random samples. Random points are generated (Figure 28) (with a help of Geospatial Modelling Environment software that uses R i386. 3.2.3 statistical software within) using a simple rejection method algorithm where potential points are generated within the rectangular boundary that defines the area of interest based on a bivariate uniform random distribution.

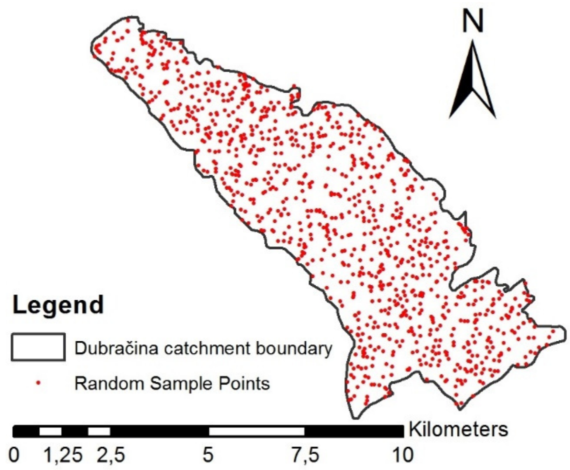


Figure 28: Case study random sample distribution

The generated points provided the sample group for which the descriptive statistics was made as a first step of the analysis. As seen in the Table 25 each parameter is characterised by its minimal, maximal value, standard deviation, as well as 95% confidence level showing mean value range and tolerance intervals showing the value range that is likely to contain 95% of the samples. If source-varying parameters are observed it can be seen that both soil erodibility coefficients based on Pedological and on Geological map differ in their value range where maximal values should be emphasized because of the higher fluctuation in value between the two sources.

Soil protection coefficient that is both source and time-varying parameter shows significant similarity between the two data set: Corine and Spatial plan. Their only difference is maximal values while all other descriptive statistic parameters remain the same. However, Landsat data differs in most categories with the Corine and Spatial Plan. The minimum value should be excluded from this statement because the evaluation of a coefficient doesn`t allow values smaller than 0.05.

Table 25: Descriptive statistics of a model parameters based on sample size

Parameters:		Minimum	Maximum	Standard deviation σ	95% Confidence level of a mean			95% tolerance intervals		
					Lower bound	Mean	Upper bound	2.5th	50th	97.5th
Average annual temperature	$T_{0\,(1961-1990)}$	8.1	13.8	1.37	11.66	11.74	11.83	8.40	12.10	13.3
	$T_{0\,(1991-2020)}$	9.0	14.7	1.32	12.65	12.73	12.82	9.30	13.10	14.2
Average annual precipitation	$P_{a\,(1961-1990)}$	1299.5	2273.5	211.7	1604.1	1617.2	1630.3	1381.9	1526.5	2192.0
	$P_{a\,(1991-2020)}$	1350.6	2329.4	205.5	1646.9	1659.7	1672.4	1437.8	1582.4	2247.9
Soil erodibility coefficient	$Y_{Pedology}$	0.10	0.748	0.123	0.61	0.60	0.59	0.43	0.565	0.75
	$Y_{Geology}$	0.25	0.60	0.129	0.36	0.37	0.38	0.25	0.25	0.60
Soil protection coefficient	$X_{a(Corine)}$	0.05	0.80	0.21	0.34	0.35	0.36	0.05	0.20	0.80
	$X_{a(Spatial\ Plan)}$	0.05	1.00	0.23	0.33	0.35	0.36	0.05	0.20	0.80
	$X_{a(Landsat\ 8)}$	0.05	0.95	0.34	0.61	0.63	0.65	0.05	0.50	0.95
	$X_{a(Landsat\ 4,5)}$	0.05	0.95	0.31	0.69	0.71	0.72	0.05	0.95	0.95

Each scenario generated three model outputs and the same descriptive statistic was made for them (Table 26) pointing out the Scenario V with greatest variance in values in comparison with Scenario I. The change between the two Scenarios is a result of data set source change from Landsat 8 to Corine land cover.

Table 26: Descriptive statistics of a model outputs based on sample size

Model outputs:	Scenario:	Minimum	Maximum	Standard deviation σ	95% Confidence level of a mean			95% tolerance intervals		
					Lower bound	Mean	Upper bound	2.5th	50th	97.5th
Total annual volume of detached soil W_a	I	0.11	275.51	14.24	15.08	15.96	16.84	0.63	13.50	45.73
	II	0.10	267.25	13.88	14.71	23.82	16.43	0.61	13.08	44.39
	III	0.10	265.49	13.74	14.57	23.62	16.27	0.61	12.98	44.15
	IV	0.11	58.00	6.65	7.90	13.52	8.72	0.80	6.15	29.30
	V	0.11	145.01	7.96	8.25	13.14	9.23	0.80	5.88	26.54
	VI	0.11	145.01	11.51	16.43	26.20	17.86	0.88	15.59	42.87
	VII	0,00	137.76	7.97	8.77	9.27	9.76	0.40	8.30	23.62
Erosion coefficient Z	I-III	0.00	4.19	0.23	0.25	0.41	0.28	0.01	0.22	0.69
	IV	0.00	0.88	0.12	0.13	0.23	0.15	0.01	0.10	0.51
	V	0.00	2.21	0.13	0.14	0.22	0.15	0.01	0.10	0.43
	VI	0.00	2.21	0.19	0.27	0.43	0.29	0.02	0.26	0.67
	VII	0.00	2.09	0.13	0.15	0.15	0.16	0.01	0.14	0.41

Actual sediment yield G_y	I	0.00	22.47	2.17	1.21	2.27	1.48	0.00	0.49	6.81
	II	0.00	21.66	2.09	1.17	2.20	1.43	0.00	0.48	6.56
	III	0.00	21.77	2.11	1.17	2.20	1.43	0.00	0.48	6.59
	IV	0.00	11.07	1.55	0.89	1.70	1.08	0.00	0.23	5.20
	V	0.00	5.14	0.86	0.56	1.03	0.67	0.00	0.27	3.11
	VI	0.00	17.53	2.15	1.30	2.41	1.57	0.00	0.47	6.77
	VII	0.00	15.56	1.53	0.81	0.90	1.00	0.00	0.26	4.62

8.2.1 Time-variant uncertainty

Analysed time-variant uncertainty refers to the three main model parameters: (i) Average annual temperature, (ii) Average annual precipitation and (iii) Soil protection coefficient based on Landsat data scene. For all three parameters cumulative probability distribution (Figure 29 and 30) was derived for two time periods, first representing past time (1961-1990) and second representing present time (1991-2020). The probability distribution for both time periods are similar for all three parameters. The 2.5th and 97.5th percentile for Average annual precipitation and temperature differs proportionally to the increase in their values in time shown earlier.

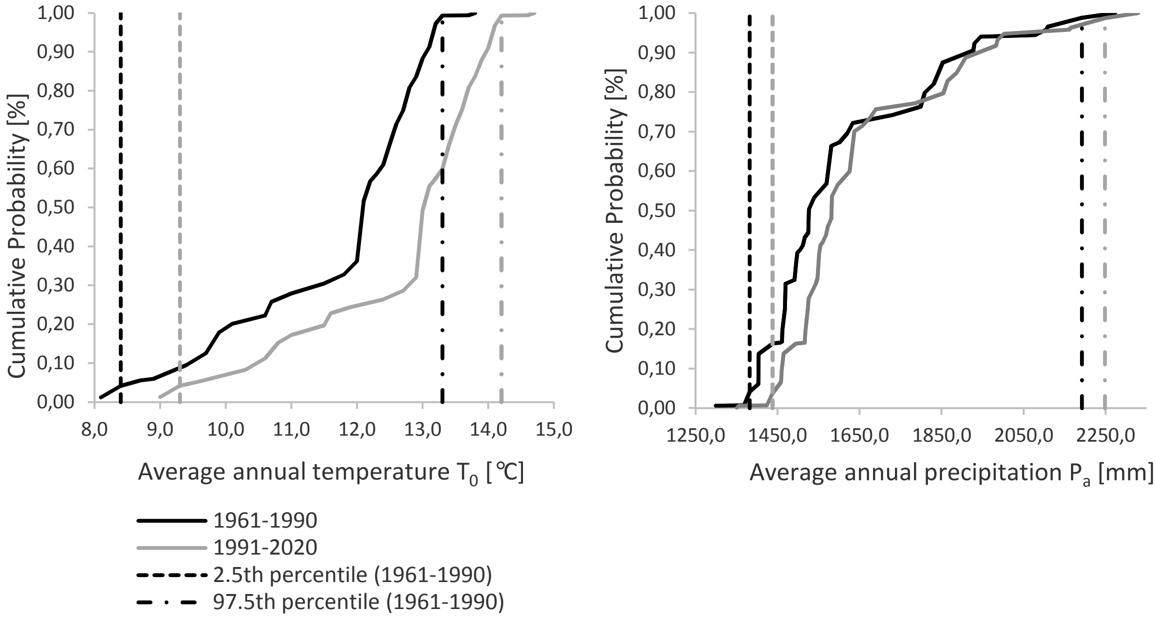


Figure 29: Cumulative probability distribution showing 95% tolerance level for time-variant model parameters temperature and precipitation

The probability distribution for both time periods are similar for all three parameters. The 2.5th and 97.5th percentile for Average annual precipitation and temperature differs proportionally to the increase in their values in time shown earlier.

For example, there is a 2.5% probability that the Average annual precipitation for the time period 1991-2020 will be 1437.8 mm or less and 97.5% probability that it will be 2247.9 mm or less for the same time period. The same probability for the time period 1961-1990 are 1381.9 mm or less for 2.5th and 2192 mm or less for 97.5th percentile.

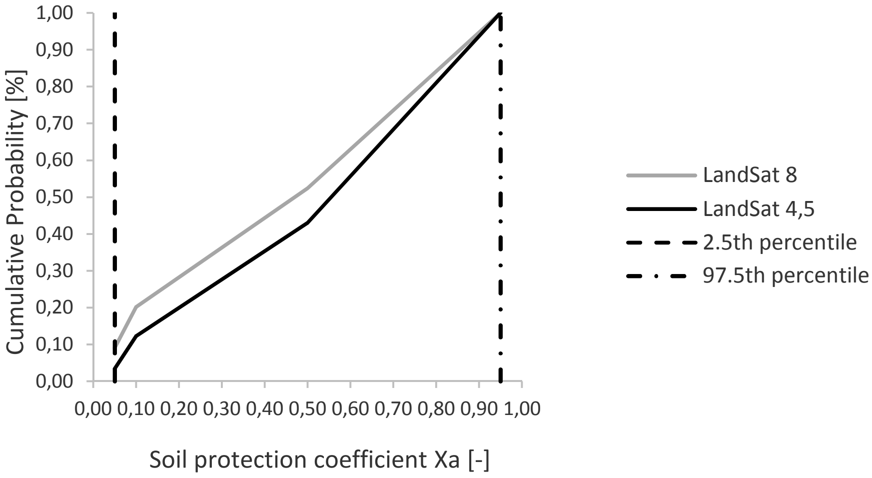


Figure 30: Cumulative probability distribution showing 95% tolerance level for time-variant model parameters soil protection coefficient

Soil protection coefficient for both time periods has the same values for 2.5th and 97.5th percentile but their cumulative probability distribution differs indicating lower probability for the occurrence of the same value for two time periods, past being represented by Landsat 4, 5 scene and present by Landsat 8 scene. The difference in all three parameters can be related to 30-year time difference that reflects climate changes in the area.

The parameter distributions were complemented by cumulative probability distributions for model outputs (Figure 31 and 32) affected by each time-variant parameter.

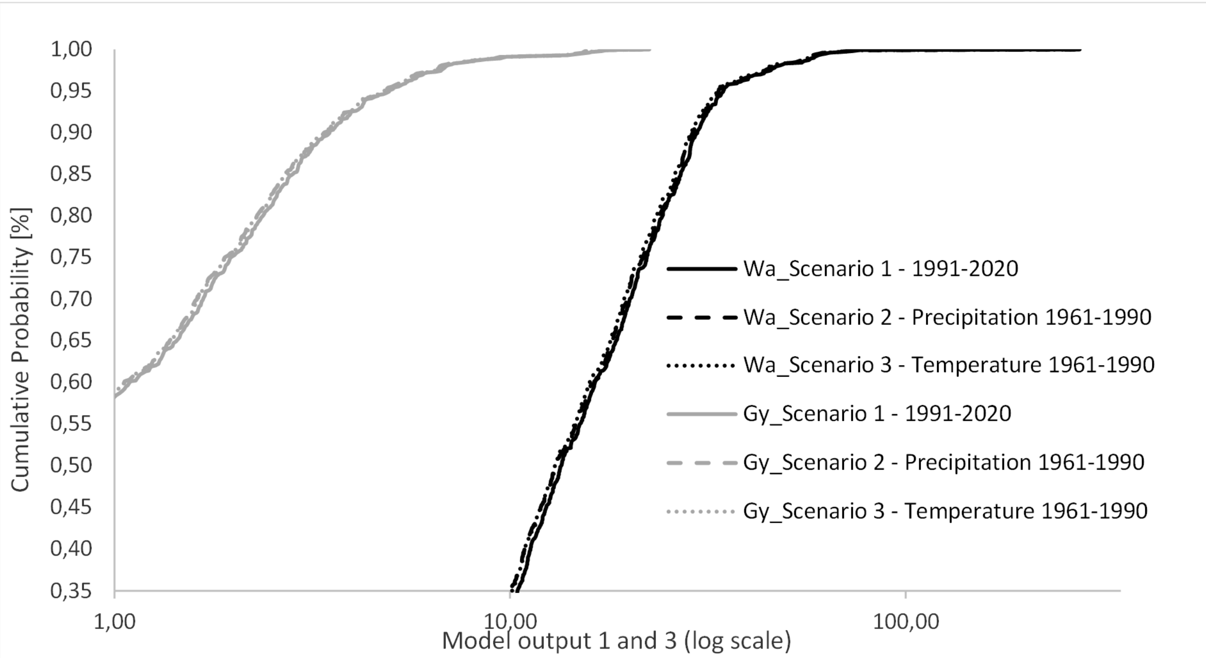


Figure 31: Cumulative probability distribution of model outputs W_a and G_y showing time-variant scenarios with temperature and precipitation parameter data change

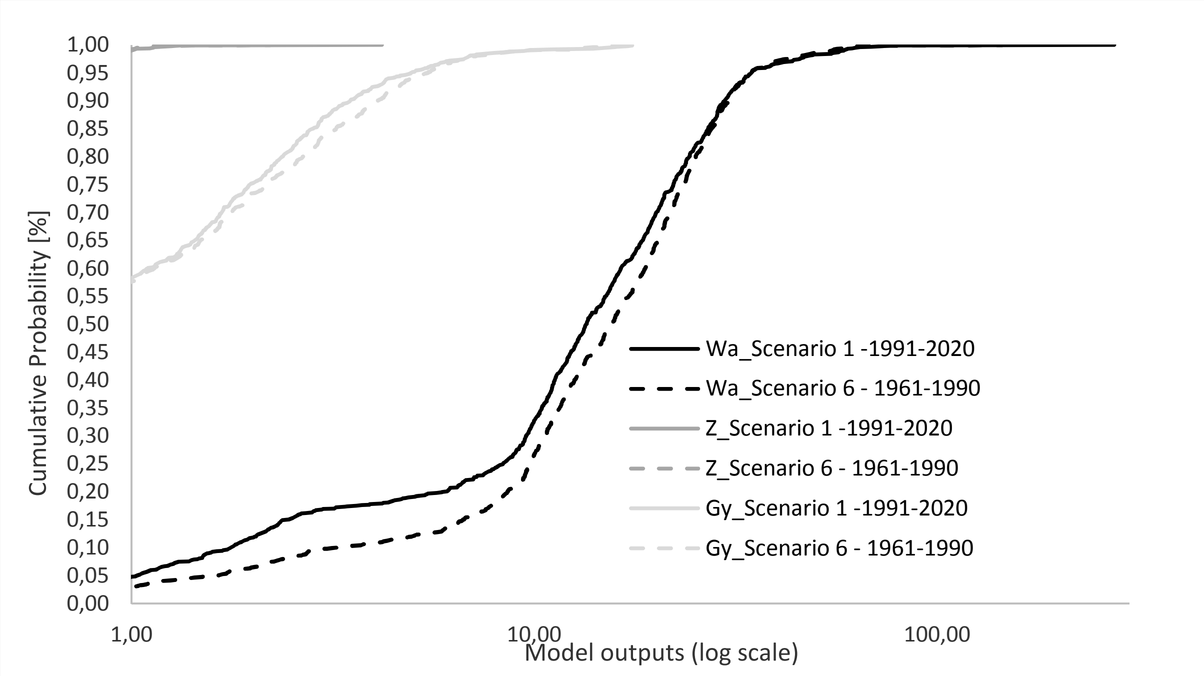


Figure 32: Cumulative probability distribution of model outputs W_a, G_y and Z showing time-variant scenarios with soil protection parameter data change (Landsat data)

Both temperature and precipitation affect only Total annual volume of detached soil W_a and Actual sediment yield G_y while soil protection coefficient affects all three model outputs. The change in temperature and precipitation distribution is small while the difference in probability distributions of the model outputs when considering the change in soil protection coefficient is more accentuated.

8.2.2 Source-variant uncertainty

The source-variance of the model parameters is not often mentioned within literature. In the case of Dubračina River catchment, where there was no previous existence of information database, during the extensive research and data collection author of this thesis has come across several data sources for the same parameter. The need to choose one as the most appropriate has stressed the need for uncertainty analysis to properly evaluate each one and acknowledge the difference between them. The cumulative probability distribution (Figure 33) was derived for both source-variant parameters analysed in this paper (Soil protection coefficient $X_a$and Soil erodibility coefficient Y).

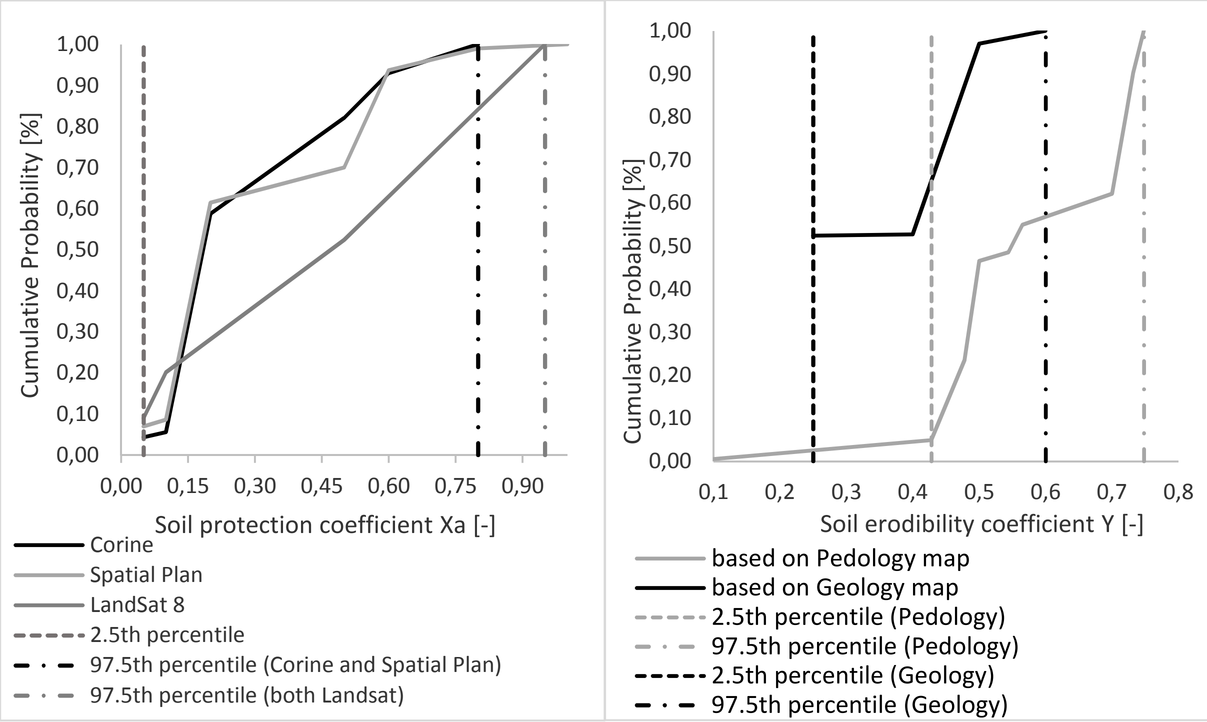


Figure 33: Cumulative probability distribution showing 95% tolerance level for source-variant model parameters

As seen in Figure 33 cumulative probability distributions for parameter X_a differs significantly when comparing Spatial Plan and Corine with Landsat scene. The approach to Spatial Plan map and Corine land cover was similar (both took into account topographic maps of the area) while the Landsat data set based on remote sensing technology was obtained from the classification of earth satellite images.

The two data sources for Y (pedology and geology map) give different cumulative probability distributions. The one based upon Pedology map is more detailed in their soil type category description than the Geology map which is something the decision maker needs to take into consideration although the scale of the geology map is more detailed than the scale of pedology map.

The cumulative probability distributions of model outputs (Figure 34 and 35) affected by both source-variant parameters show significant oscillations is its values.

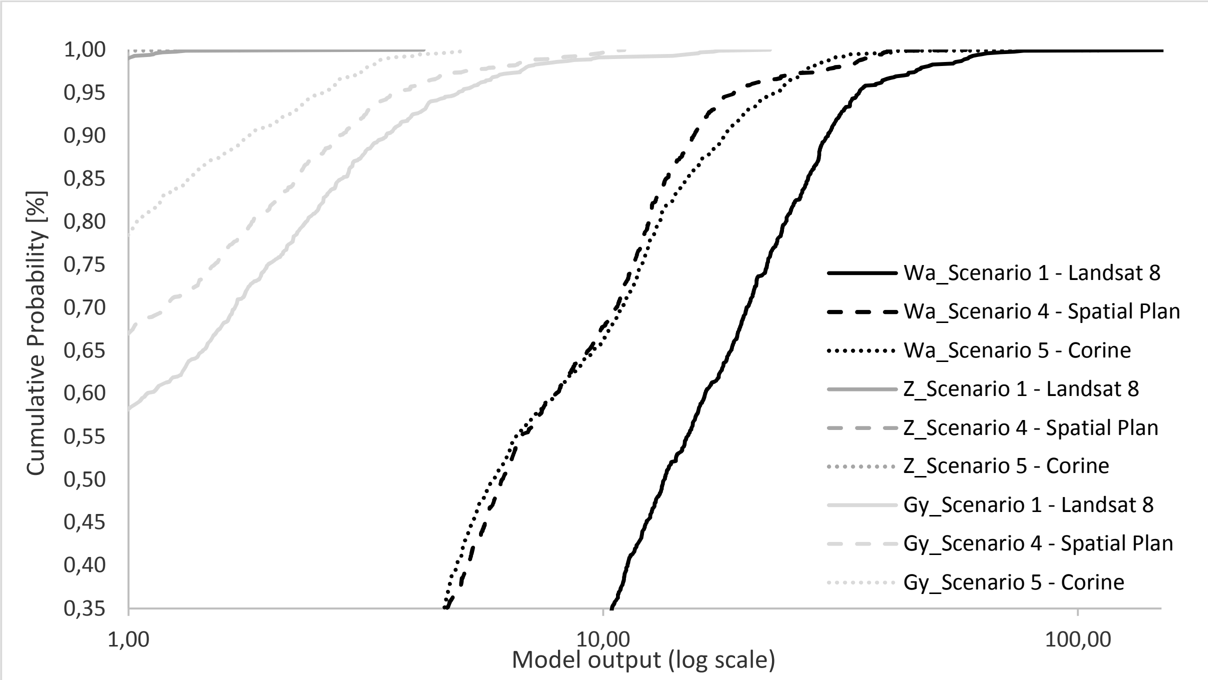


Figure 34: Cumulative probability distribution of model outputs W_a, G_y and Z showing source-variant scenarios based on land cover/use data set change

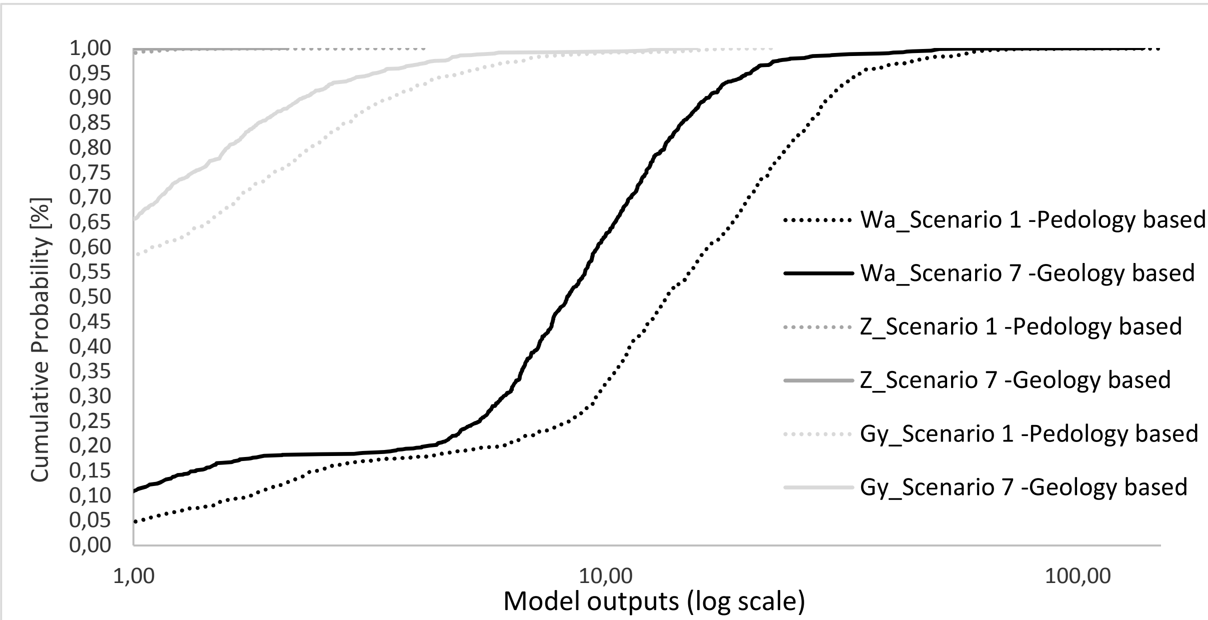


Figure 35: Cumulative probability distribution of model outputs W_a, G_y and Z showing source-variant scenarios based on soil erodibility data set change

8.3 Erosion Potential (Gavrilović) Method sensitivity analysis

Numerous studies (such as Tucker, 2004, Tucker and Whipple, 2002, van Griensven et al, 2006, Jetten et al., 1999 and 2003) applied sensitivity analysis on various erosion models such as MPSIAC (Behnam and Parehkar, 2011), CREAM (Lane and Ferrira, 1982), EUROSEM (Veihe and

Quinton, 2000), WEPP (Nearing et al., 1990), PSEM-2D (Nord and Esteves, 2005), USLE (Liu and Liu, 2010, Tattari and Bärlund, 2001), GUEST (Misra and Rose, 1996), ANSWERS (de Roo et al., 1989), etc.. Furthermore, White and Chaubey (2005) used sensitivity analysis to identify parameters that most influence predicted flow, sediment and nutrient outcomes for The Soil and Water Assessment Tool (SWAT) model. Lenhart et al. (2002) applied two different approaches to sensitivity analysis on the same model (SWAT). Sensitivity analysis was conducted for the hydrological and soil erosion model LISEM (the Limburg soil erosion model) by de Roo et al., (1992). Mendicino (1999) used sensitivity analysis on different GIS-based methodologies to estimate the Length-Slope factor in order to determine which of these is more reliable for spatial erosion risk assessment.

The analysis in this chapter comprises the Gavrilović method sensitivity analysis (Dragičević et al., the article in press). The objective of this research and analysis is to explore the constraints of the Gavrilović method and its response deriving from the change in each individual parameter in attempt to provide a better understanding of the method, the weight and contribution of each parameter in the overall method output. The analysis in this chapter is based on the case study for the Dubracina catchment area, Croatia.

8.3.1 Methodology and input data

Ballio et al. (2010) on the example of Tartano basin, Italy conducted sensitivity analysis of the Gavrilović method for only three parameters: (i) Soil protection coefficient X_a, (ii) Soil erodibility coefficient Y and (iii) Coefficient of type and extent of erosion ϕ with the parameter value deviation of -25% for X_a, +11% for Y and +6.2% for ϕ in relation to values defined by the base case scenario. The authors noted the differences between the obtained values for model outputs, ranging the values for the Actual sediment yield G_y from +5 to -35%, the first being the result of a change in parameter ϕ and later in parameter X_a. Dragičević et al. (2014) analysed uncertainties in the magnitude and spatial distribution of annual sediment production predictions in the Dubračina catchment, Croatia, where several alternative land cover/use inputs were applied. They used three different land cover/use data sets: a CORINE land cover map, a Spatial Plan, and a Landsat 8 scene and demonstrated the variations in the Gavrilović method output caused by different land cover/use inputs. The analysis shown in this chapter includes sensitivity analysis of all Gavrilović method parameters in relation to the following erosion model outputs: (i) the degree of annual soil loss (W_a), (ii) erosion intensity (Z) and (iii) eroded material transported through the river network (G_y). The analysis includes the calculation of the dimensionless Sensitivity Index I (Equation 10; (Lenhart et al., 2002) for each of the fourteen method parameters in relation to different model outputs. The dependence of model output *y* on any parameter *x* can be expresses as the partial derivative $\frac{\partial y}{\partial x}$. The approximation of this derivate is (Equation 17):

$$I` = \frac{y_2 - y_1}{2\Delta x} \qquad (17)$$

where $\pm\Delta x$ is the variation in each parameter in relation to its value in the base model variant x_0 (Equations 18 and 19) and y_1 and y_2 are calculated model outputs for the defined parameter variation.

$$x_1 = x_0 - \Delta x \qquad (18)$$

$$x_2 = x_0 + \Delta x \qquad (19)$$

Further, the calculated index $I`$ must be normalised to obtain the sensitivity index I (Equation 20):

$$I = \frac{\frac{y_2 - y_1}{y_0}}{\frac{2\Delta x}{x_0}} \qquad (20)$$

The approach to sensitivity analysis and the deviation in parameters differ for different sensitivity methods and for different case studies. The differences in parameters encompassed by sensitivity analysis can vary for e.g. from 10 or more percent in parameter value and up to one or several time multiplied values of parameters standard deviation (see Hamby 1994 and 1995, Frey and Patil 2002, Satelli et al. 2008, Cariboni et al. 2007). The sensitivity index for each parameter, using the approach proposed by Lenhart et al. (2002), is calculated such that only the parameter being evaluated is varied by $\pm 10\%$ while all other parameters remain the same as in the base model variant. Each sensitivity index is then assigned a sensitivity class (Table 27) according to its resulting values for each individual parameter (Table 29) in relation to the output of the model.

Table 27: Sensitivity classes for Sensitivity index I (Lenhart et al., 2002)

Class	Index	Sensitivity
I	$0.00 \leq \lvert I \rvert < 0.05$	Small to negligible
II	$0.05 \leq \lvert I \rvert < 0.20$	Medium
III	$0.20 \leq \lvert I \rvert < 1.00$	High
IV	$\lvert I \rvert \geq 1.00$	Very high

The necessary data can be subdivided into spatially variant input parameters (land use/cover, precipitation, temperature and land cover, soil erodibility, average slope of the study area, coefficient of type and extent of erosion and mean difference in elevation of the study area) and spatially invariant parameters (study area, perimeter of the watershed, length of the principal waterways and cumulated length of the principal and the secondary waterways). The input parameters used in this analysis were previously described in the Chapter 6. Only the parameters for which more than one input option is available are specified in more detail. Those parameters are: (i) the spatial distributions maps for precipitation and temperature chosen for the present time (1990-1961), (ii) the soil erodibility coefficient based on a pedological map of Primorsko-Goranska County, with a scale of 1: 100,000, (iii) the soil protection coefficient based on the Landsat 8 data with a cell size 15x15 m.

8.3.2 Method sensitivity analysis results

For the Gavrilović method sensitivity analysis (Dragičević et al., the article in press), twenty-nine model variations were derived, and a total of fourteen model parameters were analysed and varied by ±10% to obtain the values for the Sensitivity index I for each affected model output (Table 23). The included parameters can be divided into three categories: (A) the parameters that affect all three model outputs (W_a, G_y and Z), (B) the parameters that affect both W_a and G_y, and (C) the parameters that only affect G_y.

The parameter with the highest sensitivity for all model outputs is the soil erodibility coefficient Y, followed by the soil protection coefficient X_a. Although overall X_a is a parameter with a very high sensitivity to the model, its slightly lower value compared to W_a classifies it as high-sensitivity model parameter. All B category parameters are considered to be in the very-high- or high-sensitivity class in addition to the Average annual temperature T_0. It is well known that temperature and precipitation have a large impact on erosion processes, precipitation more than temperature within the climate area for which the model was primarily developed. As expected, the model sensitivity class for the Average annual temperature T_0 is lower than the Average annual precipitation P_a but, when the Average annual temperature T_0 is transformed into its related form as the Temperature coefficient T, its sensitivity class is upgraded by one class.

Table 28: Results of sensitivity analysis for Gavrilović model parameters in relation to model outputs (Dragičević et al., the article in press)

Parameter	Units	Sensitivity class calculated in relation to model output (calculated value for Sensitivity index I)			Category
		Wa (m^3/year)	Z (-)	G_y (m^3/year)	
Y	(-)	IV (1.00)	IV (1.01)	IV (1.01)	A
X_a	(-)	III (0.99)	IV (1.00)	IV (1.00)	
J_a	(%)	III (0.39)	III (0.39)	III (0.35)	
ϕ	(-)	II (0.19)	III (0.20)	III (0.29)	
T	(-)	IV (1.01)	-	IV (1.01)	B
Z	(-)	IV (1.00)	-	IV (1.00)	
P_a	(mm)	III (0.99)	-	IV (1.00)	
F	(km^2)	III (0.99)	-	IV (1.00)	
T_0	(°C)	III (0.45)	-	III (0.46)	
ξ	(-)	-	-	IV (2.23)	C
D_d	(km/km^2)	-	-	III (0.99)	
O	(km)	-	-	III (0.50)	
z	(km)	-	-	III (0.50)	
l_p	(km)	-	-	II (0.17)	

The category C parameter with a very high sensitivity is the Sediment delivery ratio ξ, which is a product of all other category C parameters included in the analysis, all of which are in the high model sensitivity class except for the Length of the principal waterway l_p, with medium sensitivity.

8.3.4 Discussion and conclusions deriving from sensitivity analysis

Summarising the analysis, sensitivity classes were assigned for each of fourteen different parameters included in the method, with the objective of providing a better understanding of the method and the contributions of each parameter to different model outputs. The model outputs are mainly based on the multiplication of the model parameters; thus, for example, when varying the Average annual temperature P_a, the model outcome Total annual volume of detached soil W_a will vary proportionally. Not all parameters are included in the model through multiplication, e.g., Average slope off the study area J_a, Average annual temperature T_0 and Drainage density D_d. Most of these parameters are categorised as high or medium sensitivity, whereas those in the multiplication form are classified as very-high-sensitivity parameters (Dragičević et al., the article in press).

It is for a discussion if coefficient of type and extent of erosion ϕ should have less impact upon method outputs. Although sensitivity of the method output W_a in relation to ϕ is medium, its effect on Z and G_y remains clasified as high. This parameter, although usefull, is one of the parameters that is not as commonly used as input parameter in other similar methods for erosion sediment assessment. The same can be said for O, z and lp, la and L representatives of the study area characteristics, that highly affect G_y. Ballio et al. (2010) conducted the sensitivity analysis of the Gavrilović method for parameters ϕ, Y, X_a but have left out a conclusion about the sensitivity parameter ranking. Nevertheless, they noted significant changes in model output values caused by the change in input parameters, particularly soil protection coefficient X_a which is according to sensitivity analysis conducted on example of Dubračina catchment area high to very high sensitivity parameter. Soil erodibility coefficient Y and soil protection coefficient X_a are considered very high sensitive parameter with $X_a$being high sensitive parameters in relation to W_a model output. Dragičević et al. (2014a) analysed effect of using different information sources for land use/cover parameter X_a and noted significant deviation in model output values. Although, their analysis explores the parameter uncertainty in a model it is also closely related to parameter sensitivity analysis since both analysis take into consideration the deviation in a parameter value, whether intentionally choosing the percentage for which its value will differ or choosing among various data whose deviation is defined by other external factors (Dragičević et al., the article in press).

The second thing that could be taken into consideration during model calibration and modification in order to mitigate model errors and uncertainties is whether or not average annual temperature is given high enough significance in the model. The question is if the integration of T_0 in this way in the method restricts its use only within the areas of similar climate. Both precipitation and temperature are considered to be highly significant by world scientific literature whereas within the Gavrilović method temperature is mitigated thought the temperature coefficient.

Average slope length and gradient of the study area has a great impact upon water erosion, runoff and downslope sediment transport and as such represent study area topography (Kinnell, 2000, Shi et al. 2012, Blanco and Lal 2008). This parameter`s (J_a) impact upon a method outcome is high but according to its calculated values for sensitivity index I, J_a falls within parameters with lower high sensitivity class values.

All this parameters could potentially be used in future research where the need for its modification and method calibration presents for a research areas with different characteristic (e.g. climate, geological, etc.) than those applied to this day.

Van Griensven et al. (2006) indicated the dependence of parameter sensitivity ranking, for higher ranked parameters, on the variable, the location and case study. They highlight the need for the sensitivity analysis to be conducted on each new catchment study in order to select a subset of parameters to be used for model calibration or/and uncertainty analysis.

Overall, the most sensitive model parameters resulting from conducted sensitivity analysis for Gavrilović method are also those considered to be significant in the scientific literature on erosion (e.g. Morgan, 2005; Toy et al. 2002, etc.).

8.4 Discussion and population uncertainty

The source change in an input data set is a direct indication of model uncertainty and can mislead model developers into false conclusions about the existence of model error while not considering “human” error. Human error concerns the development of different sets of the same data for various purposes and by various governmental and non-governmental institutions in the absence of data interchange and joint national databases for similar data. When using multiple sources for the same data, model developers will find themselves having to choose the most appropriate data source. The selected criteria are determined on a case-by-case basis. Such criteria can include information about the expertise of the data set developer, the resolution of the data set or even the purpose for which data was generated and its relation to its project.

This analysis has an aim to emphasize such problems related to "human" error made by decision makers and all the experts involved when choosing among multiple data set. The indication of the deviations, taking into consideration the entire population, in model output values when different input data sets are used is shown in the Table 29.

Table 29: Model uncertainty shown in percent change in the model output

Parameter	**Change in parameter data set [%]**	**Change in model output values**		
		[%$W_{a.I}$]	[%Z_I]	[%$G_{y.I}$]
Average annual precipitation P_a	-2.5	/	-2.4	-3.5
Average annual temperature T_0	-3.3	/	-3.4	-3.2
Soil protection coefficient X_a (source Spatial Plan)	-45.5	-46.0	-46.9	-23.5
Soil protection coefficient X_a (source Corine database)	-45.0	-45.0	-44,7	-50.9
Soil protection coefficient X_a (source Landsat 4,5)	-2.5	+9.9	+9.8	+11.8
Soil erodibility coefficient Y	-37.8	-41.2	-41.7	-33.9

Taking for example Soil protection coefficient based on the Landsat 8 scene in the first case scenario (I) based on Landsat 8 scene in comparison to the same coefficient based on different data source. This parameter when based on Corine dataset deviates by 45% in relation to that based on Landsat 8 data set. The 45% change in dataset causes 44.7% change in Total annual volume of the soil W_a model output, 45% change in Erosion coefficient Z output and 50.9 % change in Actual sediment yield G_y output. This parameter when reviewing all available data set is the one that affects the model outputs the most and according to sensitivity analysis is a parameter with very high sensitivity on model. The next parameter with a very high sensitivity and with significant output value deviations is Soil erodibility coefficient Y. The two available data sets differ by 37.9% and cause the difference in model output values from 33.9 up to 41.7 %. Both parameters indicate problems related to source-varying parameters. Time-varying parameters average annual precipitation, average annual temperature and soil protection coefficient (Landsat based) contribute less to model output change. That is expected and is the indication of climate change in 30 (thirty) year time period on the area of interest.

The large percent change in the model outputs for source-varying parameters is associated with human error and can lead to disproportional and unrealistic estimations of erosion soil loss in the area of interest and as such relates to model uncertainty. The spatial variance of the model outcome for Erosion coefficient Z is shown in Figure 36.

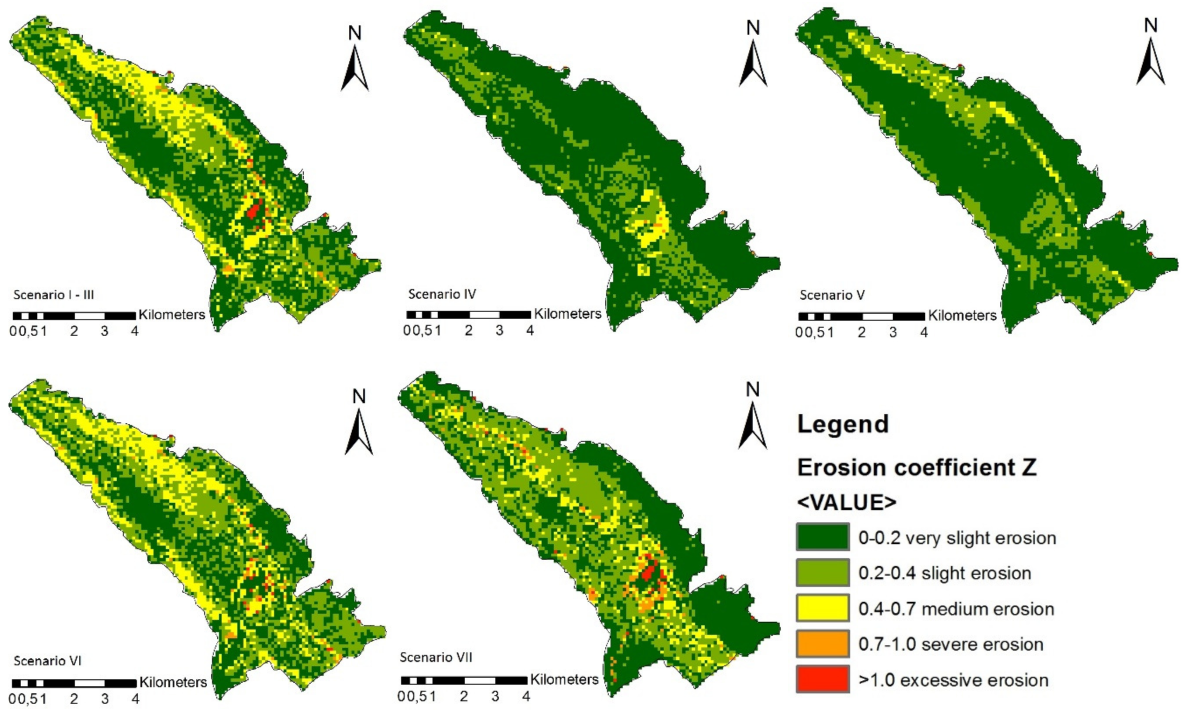


Figure 36: Spatial change in the model output Erosion coefficient Z values for different scenarios

If the "the purpose for which data was made and its relation to its project" criterion is considered, then the Landsat data set that is used for the purpose of land cover analysis for Dubračina catchment is considered to be the best choice while Spatial Plan is considered to be the least reliable. Furthermore, if a decision maker considers that the Corine land cover map for the Dubracina catchment area is unchanged over a 10-year time period and that the Landsat data set points to the existence of land cover changes in the same period, Landsat data are evidently to be chosen as most relevant for further model estimations. Also, the Landsat data provides the highest resolution. For the soil erodibility coefficient Y Pedology map was chosen as the most reliable. Although this map provides lower resolution than the Geology map, it compensates with more detailed description of the soil characteristics for the area upon which the soil erodibility coefficient can be determined.

8.5 Conclusion

The conducted analysis explained in detail in this chapter had the aim to attempt to provide answers to several of the questions mentioned in the introduction. The analysis consisted of seven model scenarios, each changing only one parameter. The influence of four different parameters were analysed, namely, (i) average annual temperature, (ii) average annual precipitation, (iii) soil protection coefficient and (iv) soil erodibility coefficient, where the first three are time and source-varying parameters and the fourth is considered to be only a source-varying parameter.

Incorporating quantitative uncertainty analysis into modelling can provide a major tool for decision making process especially when dealing with a large variety of data and multiple data sources for the same input. Uncertainty analysis has an aim to provide the estimation of potential sources of uncertainty and their importance as well as the ranking of contributors to a model uncertainty. Indicating from it source-variant parameters have shown to have a greater impact upon a model outcomes and both soil protection coefficient and soil erodibility coefficient are high sensitive model parameters all of which puts them in first ranking position as most uncertain parameters in this case study. In contrary to source-variant parameters, time-variant parameters have significantly less impact upon model and their uncertainty is related to climate change in 30-year time period.

The analysis indicates that when changing the data source, significant changes to the model outcome value (up to approximately 47% as shown on Dubračina River catchment study area) can occur without the awareness of an expert as to the nature of the error. Such changes are related to human error and depend on detailed preliminary research and data gathering as well as applied criteria for appropriate data selection.

Various criteria can be used in the decision-making process for data selection on a case-by-case basis. As an example for the Dubračina catchment, “the purpose for which data was made and its relation to its project” and “available resolution” have been chosen as the primary criteria for choosing Soil protection coefficient X_a information source. Based on those two criteria Landsat data was chosen as the most appropriate input data on which Soil protection coefficient X_a is based. Although Pedology map doesn’t provide better resolution in comparison to Geology map it is still makes a more detailed map when describing the characteristic of each soil type. That is the main reason Soil erodibility coefficient Y was chosen to be based primarily on Pedology map. The main concern in cases with different data source available and a lack of more erosion measurements is the constant uncertainty in the decision-making process and the chosen data for model prediction. This can only be confirmed with certainty after long-term comprehensive field measurements are performed.

CHAPTER 9: ANNUAL AND SEASONAL EROSION SEDIMENT PRODUCTION ON THE DUBRAČINA CATCHMENT

This chapter contains two main subsections, where the first encompasses the results from the Gavrilović model related to the estimation of the annual values for the erosion sediment production on the Dubračina catchment for two time-series, the past and the present. In the second subsection proposed modifications of the Gavrilović method are given, and related seasonal output values form a model for present time presented. Furthermore, the acceptability of the modified Gavrilović model intended for the calculation of the seasonal (3 month interval) erosion sediment production values, presented in this thesis, is discussed.

9.1 Erosion intensity and sediment production assessment on the Dubračina catchment for past and present time

The estimated values and maps derived by the Gavrilović model, representing the erosion intensity or Erosion coefficient Z, Total annual volume of the detached soil W_a and Actual sediment yield G_y, are based on the input data described in more detail in Chapter 6. The input data that differs for both time-series, the past (1961-1990) and the present (1991-2020) are:

i. Average annual precipitation P_a,
ii. Average annual temperature T_0 and
iii. Soil protection coefficient X_a

As mentioned in chapter 6 the Average annual precipitation P_a and the average annual temperature T_0 for the past time period (1961-1990) was obtained from the Croatian Meteorological and Hydrological Service. The input maps for the present time (1991-2020) for these two parameters were derived as described in detail in chapter 6. The soil protection coefficient for the past time is based on Landsat 4, 5 data scene from the August 1984 and for the present time on Landsat 8 data scene from the August 2013. For both time-series, pedology map was used to derive Soil erodibility coefficient Y. The differences between the past and the present input data representing one of the above mentioned input parameters are explained in more detail in the chapter 6.

Erosion coefficient Z, indicating erosion intensity in the catchment, Total annual volume of the detached soil W_a, indicating overall erosion sediment production on an annual basis, and Actual sediment yield G_y, indicating erosion sediment yield transported downstream during one year time period, were derived in a form of maps for the Dubračina catchment (Figure 36). For each output parameter (Z, W_a, G_y) two maps were generated (Figure 36), one representing the past time (time-series 1961-1990) and one representing the present time (time-series 1991-2020). The maps showing the change between the two time series for Z, W_a and G_y are presented by Figure 37a, 38a and 38b, clearly indicating the areas of increase/decrease in values. The distribution of maximum absolute change in predicted values per each sub-catchment for the same model outputs is presented in a Figure 37b, 38a and 38b. It should be noted that the values for the W_a and G_y in Figures 38 and 39 are expressed in m^3/cell/year whereas the generated model outputs W_a and G_y showing their spatial distribution across Dubračina catchment (Figure 37) are expressed in m^3/km^2/year.

As seen in Figure 37, the most noticeable spatial change in erosion coefficient Z is recorded around Slani Potok and Mala Dubračina sub-catchments, where the area encompassed by excessive erosion ($Z \geq 1.0$) has increased from past to present time (Figure 37). The change in mean values between the past and the present is around 9% showing the overall decrease in erosion intensity in the catchment during the years (Table 30) where the biggest changes are noted on sub-catchments Kučina, Leskovnik, Slani Potok, Mala Dubračina and Ričina Tribaljska (Figure 38b).

Similar changes can be noticed on the spatial distribution map, representing the Total annual volume of the detached soil W_a, between the two time periods. The average change in values throughout the catchment is found to decrease by 3% between the past and the present time, where in the past average value of the detached soil in the catchment is 15.64 m^3/cell/year which is equivalent to 1564 m^3/km^2/year, and in the present time 15.12 m^3/cell/year or 1512 m^3/km^2/year. Based on this values, it can be concluded that this change is not significant, but when the map showing spatial distribution (Figure 39a) and the absolute maximal change in W_a per sub-sub-catchment is taken into consideration, sub-catchments Leskovnik, Ričina Tribaljska, Slani Potok, Mala Dubračina and Kučina contribute the most to overall W_a values, all of them with value increase/decrease by up to several times its average values for the entire catchment.

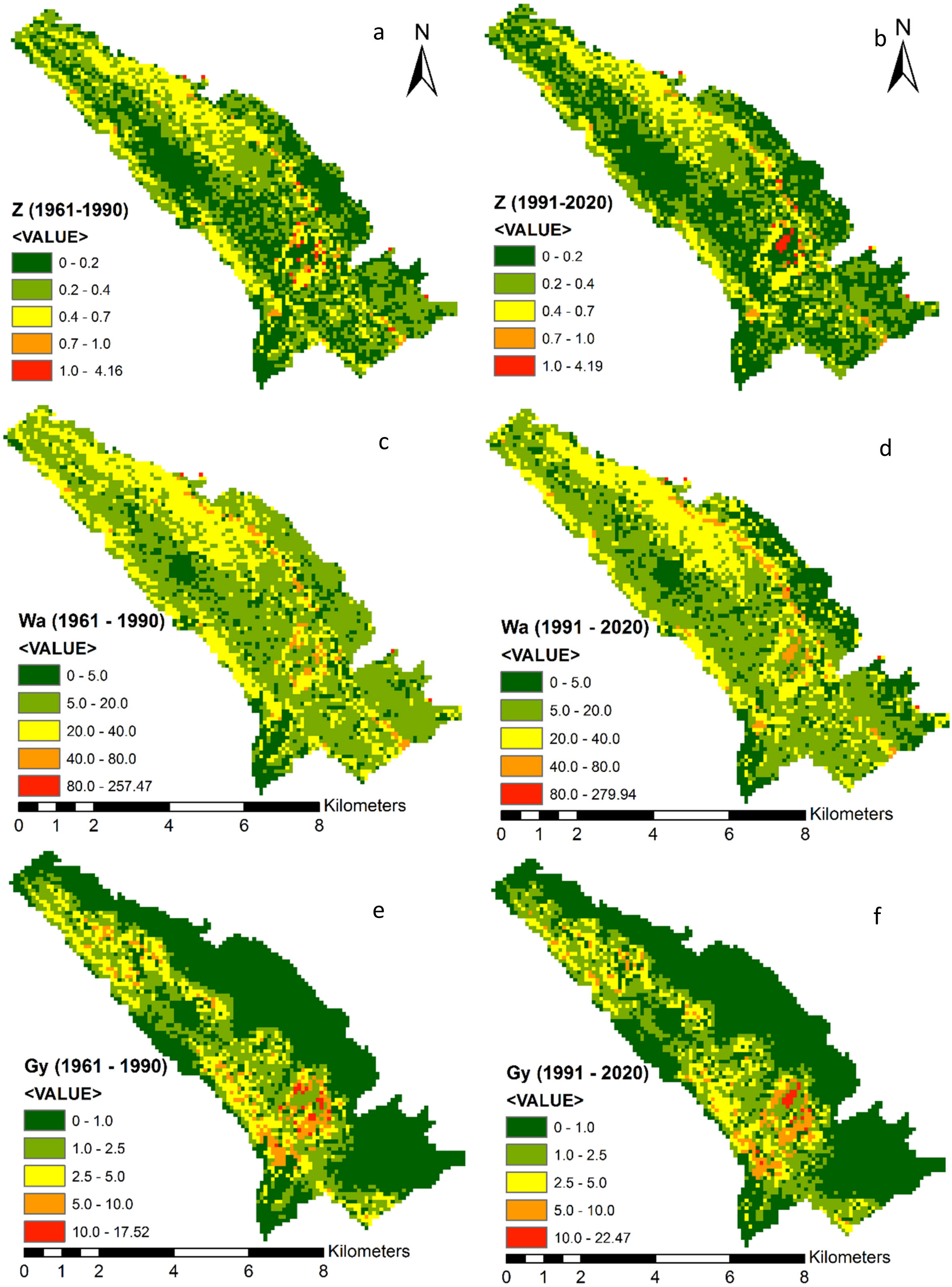


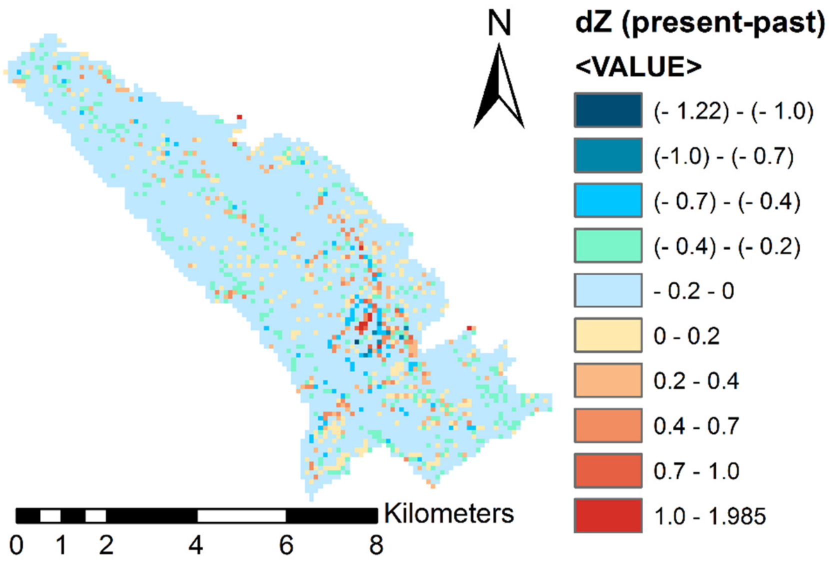
Figure 37: Gavrilović model outputs for the past and present time series for the Dubračina catchment: a) Erosion coefficient Z for the time period 1961-1990, b) Erosion coefficient Z for the time period 1991-2020, c) Total annual volume of the detached soil W_a for the time period 1961-1990 in m^3/cell/year, d) Total annual volume of the detached soil W_a for the time period 1991-2020 in m^3/cell/year, e) Actual sediment yield G_y for the time period 1961-1990 in m^3/cell/year, f) Actual sediment yield G_y for the time period 1991-2020 in m^3/cell/year

Table 30: Descriptive statistics for derived past and present model outputs (Z, W_a, G_y) for the entire catchment Dubračina

Time-series	Statistical parameter	Z [-]	W_a [m^3/cell/year]**	G_y [m^3/cell/year]**
1961-1990	Minimum	0.0009	0.044	0
	Mean	0.274	15.649	1.30
	Maximum	4.163	257.47	17.51
	Sum*	/	67 072.91*	5573.21*
	Standard deviation	0.297	11.442	1.855
1991-2020	Minimum	0.0009	0.048	0
	Mean	0.250	15.12	1.244
	Maximum	4.189	279.93	22.47
	Sum*	/	64810.75*	5331.86*
	Standard deviation	0.219	13.701	1.908

*[m^3/catchment/year]
** cell size is 100x100m or 0.01 km^2

a



b

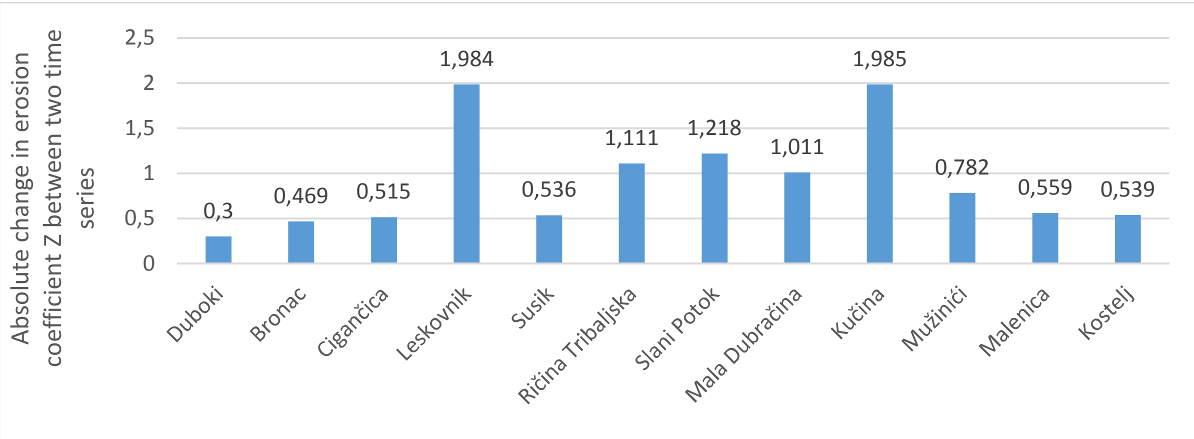


Figure 38: The change in erosion coefficient Z values between the two time-series: a) map of the “real” change in Z, b) the absolute change in Z

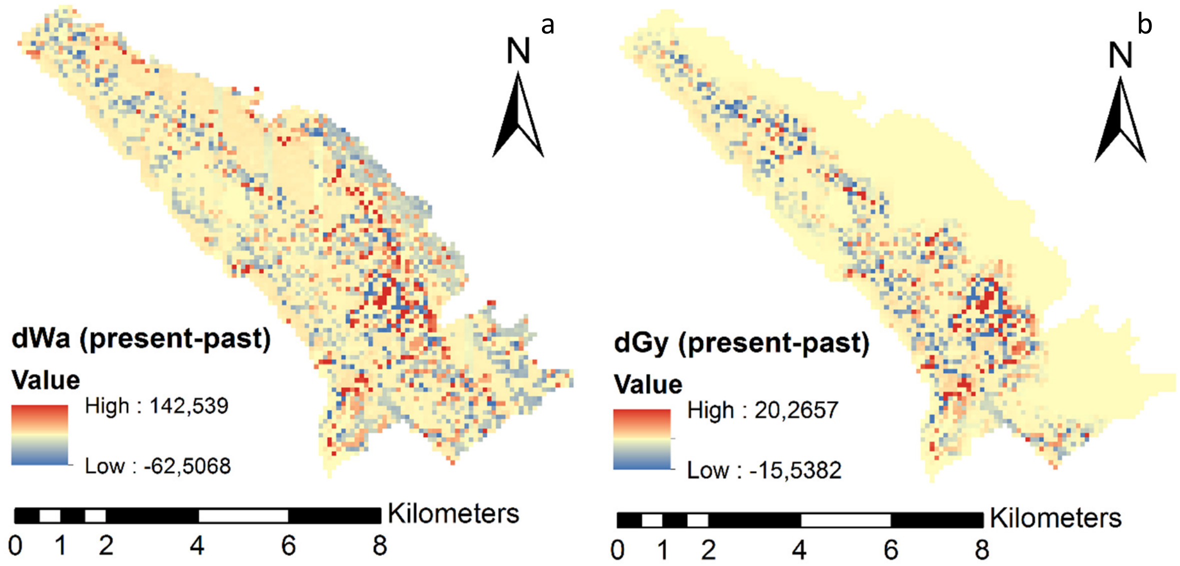


Figure 39: The "real" change between the two time series in: a) Total annual volume of the detached soil W_a and b) Actual sediment yield G_y

The sub-catchments Slani Potok and Mala Dubračina show the increase in both values for W_a and G_y, with highest noted increase in values for the G_y (Figure 40). Overall, map showing the change in G_y values indicates smallest change in values but coincide with other model outputs (W_a and Z) indicating the biggest change around the sub-catchment Slani Potok and Mala Dubračina.

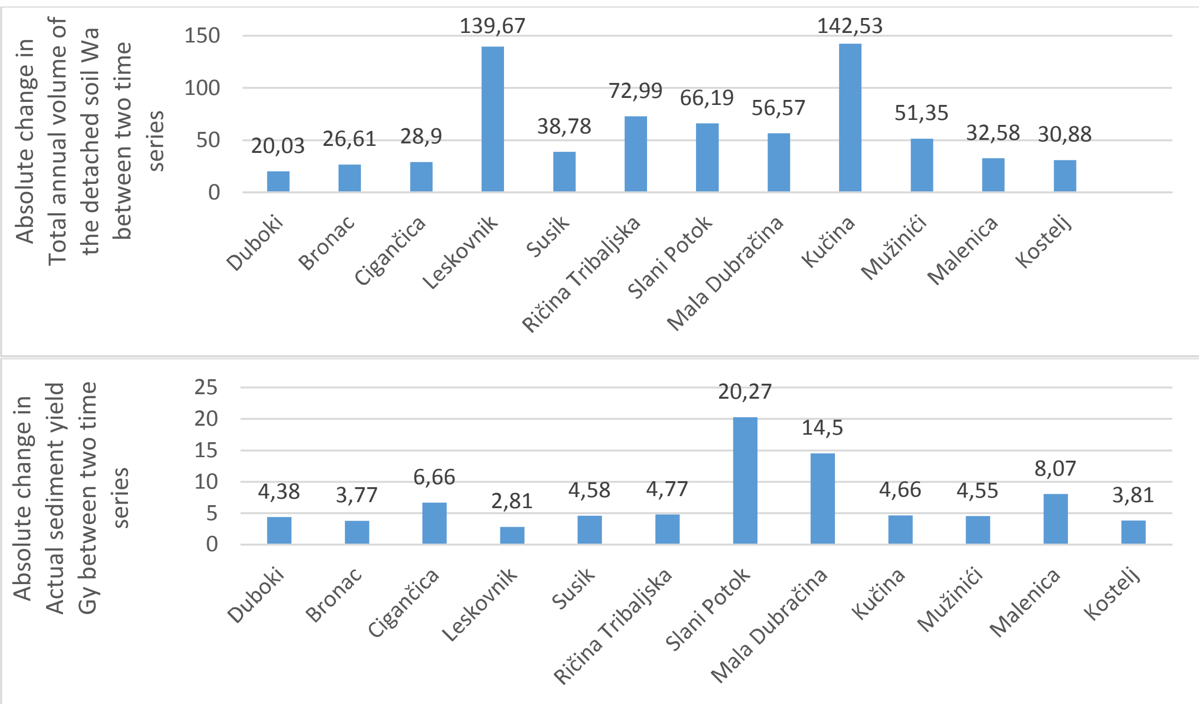


Figure 40: The absolute change in output values by each sub-catchment for: a) Total annual volume of the detached soil W_a b) Actual sediment yield G_y

The calculated values for Total annual volume of the detached soil W_a for the present time is 64 810.75 m^3/catchment/year and for the past 67 072.91 m^3/catchment/year, which indicates the decrease in erosion production by overall 3.3%. The Actual sediment yield indicates the change by 4.3%, from heaving 5 573.21 m^3/catchment/year in the past to heaving 5 331.86 m^3/catchment/year in present time.

The current erosion intensity in the catchment and the erosion sediment production and transportation is represented by the model outputs form 1991-2020 time-series. The very slight erosion covers the largest area of the catchment, approximately 44.98%, followed by slight erosion with 34.19%, then moderate erosion with 17.11%, and severe and excessive erosion covering together approximately 3.72% of the catchment area (Figure 41). Overall, average erosion coefficient for the Dubračina catchment is 0.25 which classify it as the area of slight erosion. Nevertheless, it should be noted that although its overall classification categorises erosion processes in the catchment as slight, the maximum values are reaching 4.189 which is more than 4 times higher that defined boundary value for excessive erosion class.

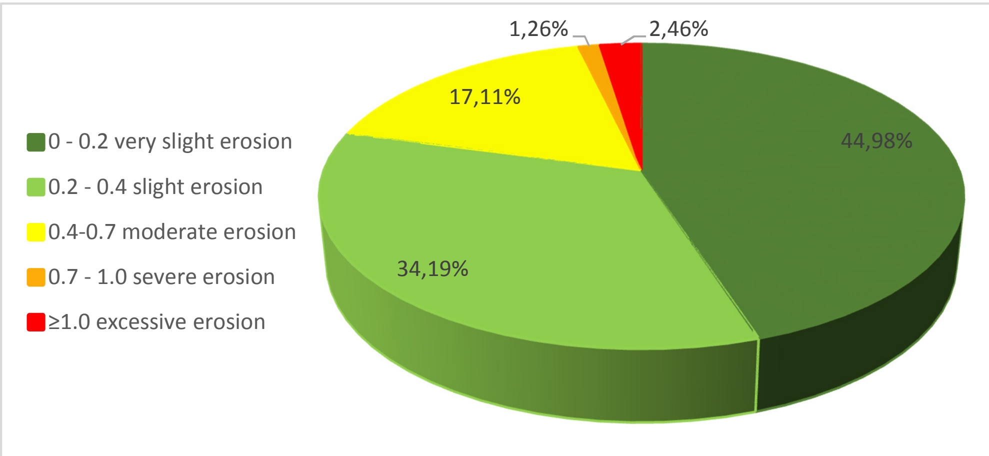


Figure 41: Erosion intensity classes expressed in percentage on the Dubračina catchment

Also, the distribution of mean values for each sub-catchment representing the Erosion coefficient Z are given in Figure 42.

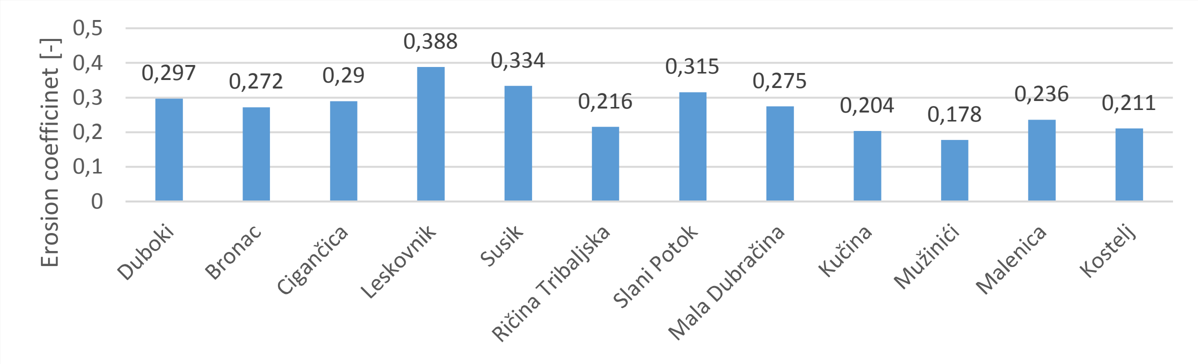


Figure 42: Mean values for Erosion coefficient Z per sub-catchment for the present time series

9.2 Estimation of seasonal erosion sediment production on the Dubračina catchment

The most often used time interval for which the erosion sediment production is calculated is one year. Although, today more and more interest is given on event based calculation of sediment production but those models are mainly complex physical based model. When choosing and applying the method and model for erosion assessment, consequently one or the other time interval for which the model was developed is chosen. However, till today, less attention is given on seasonal erosion sediment production assessments which can actually highly contribute to the planning strategies and implementation of erosion mitigation and prevention measures and benefit local community, which is one of the aim of this thesis.

One of the previous conducted researches on seasonal oscillations in sediment production included the rainfall simulation experiments and cylinder infiltrometer measurements of the erosion sediment production on three different soil types (marl, clay and sand) in the autumn and summer, representing wet and dry season in the Monnegre river catchment in the south-east Spain (Cerdà, 2002). The aim of this research was to determine the influence of season and soil type on erosion, runoff and infiltration. The results have indicated marl soil to have high erosion rates, while clay and sands have lower erosion rates. Clay and sand soils have a higher runoff and lower sediment concentrations due to the dilution of the sediment by the increased discharge, while on marl soils as runoff increases so does the sediment concentration. Overall, measured erosion sediment production was ten (10) to fifteen (15) times less on clay and sand soils than on marl soils. They concluded that the erosional processes are highly controlled by seasonal climatic fluctuations and the measurements have shown the increase in erosion sediment production during the autumn season by 5% more in marls soils, 9% on clay soils and 3% on sands soils. However, the seasonal erosion variations were not as visible due to the increase of the runoff sediment concentration during the summer season, opposite to the highest measured erosion rates in autumn.

Millward and Mersey (1999) developed a conservation tool based on RUSLE modifications for modelling soil erosion potential with regard to the unique physical and biological conditions of a Zenzontla sub-catchment of the Río Ayuquíla catchment in Mexico. They modified RUSLE model to calculate erosivity values for each season so to represent the erosive potential of precipitation for each period within a year, in opposite to the usual annual application of the RUSLE model. The GIS database and soil erosion potential maps generated in this research provide valuable planning aids based on sustainable management for land managers that need to balance environmental conservation with the social and economic development in the area. This research has helped to define the optimum timing for erosion prevention and mitigation activities in the areas identified as areas with high or extreme soil erosion potential.

Sediment production in the Vallcebre catchments, Spain (Gallart et al., 2002) is found to be highly seasonal, and characterized by physical weathering during winter season, regolith breakdown and vigorous hillslope erosion during spring and summer season, and efficient sediment transport in autumn. From spring to mid-summer, raindrop splash and later wetting-drying are found to be the main causes of slope erosion in the area. During this time, the highest sediment concentrations in rivers are measured indicating active sediment transport and sediment accumulation in the river beds and on the feet of a hillslopes. Late summer to mid-autumn is the rainiest period within a year, where sediment transport is the main process. Sediment production during the winter season was found to be scarce due to high permeability of the regolith on Badland surfaces and small precipitation energy. The increase in precipitation during the spring and the compaction of Badland regoliths caused the increase in erosion sediment production values on Badland slopes as well as sediment concentration in rivers. Decrease in sediment transport, due to small stream flow events and increase in erosion sediment production on Badland slopes are noted during the summer period. Large rainfall events in the autumn and wetting of the catchment are causing the flow events that are the main reason for eroding and transporting the sediments deposited in the earlier seasons. In their analysis, Gallart et al. (2002) noted the gradual increase in sediment transport from winter to summer time period with the peak increase in autumn, which does not coincide with the precipitation and runoff patterns, indicating changing relationship among these three variables (Figure 1)

Gallart et al. (2002) analysed the correlation between the sediment transport and various hydrogeological parameters and noted:

- high non-linearity of the erosion and sediment transport processes,
- linear correlation coefficient between suspended sediment transport and precipitation, runoff and regolith status at the monthly and seasonal scale
- sediment transport significant correlation to the total precipitation and the number of heavy storms at the monthly scale, but not at the seasonal scale
- no correlation between rainfall intensity and sediment transport at any of the analysed scales
- correlation between sediment transport and the flow characteristics of the events at temporal scales but poorer correlation at the seasonal scale
- no correlation between the sediment transport and the moisture and bulk density of badland regoliths at any scale

Monthly soil loss and runoff for different land use/cover types under climate change scenarios on Egribuk subcatchment at Seyhan catchment, Turkey obtained with PESERA model were analysed by Cilek et al. (2015). Their analysis included comparison between the present and future erosion sediment production on monthly basis and indicated the increase in sediment production from August to January during the autumn due to heavy rain and high runoff, and the decrease in sediment production during the winter. They have estimated the highest amounts or erosion sediment in the December and the lowest in June for the present time, while in the future time the lowest values estimated are in August due to high temperature and minimal precipitation.

Estimated values of soil loss in summer season in South-Limbourg, Netherlands, due to the high intensity precipitation, was found to be twice as high as winter soil loss, when the low intensity precipitation occurs. Within this research Kwaad (1991) concluded that the increase in overall summer precipitation amounts will not affect soil loss but the increase in precipitation frequency and intensity will. Opposite to summer, the increase in total precipitation amounts as well as in its intensity during the winter season will lead to the higher rates of soil loss.

The increased aridity leads to an increase in erosion potential, as shown with the research conducted by Megnounif et al. (2007) on the Upper Tafna catchment in Algeria. During the late autumn to end of spring the sediment production was found to increase in opposite to the period from Summer to Autumn. They concluded that the rare vegetation and the low soil moisture are related to the high sediment production values in autumn.

Rudra et al. (1986) presented GAMES model with an aim to provide a seasonal sediment production and sediment yield processes mainly for spring, summer and fall. The research had an aim for the model outputs to help in the process of applied mitigation strategies and programs efficiency evaluation.

Seasonal variations in soil erodibility were analysed by Coote et al. (1987) in the regions of Ontario. They concluded that soils in the Ontario region are more prone to erosion processes during the spring than in the other seasons within a year.

Within this chapter the explanation on modification of the Gavrilović method and the calculated values for season soil erosion sediment production for present time are given. There are three main parameters that are changed in relation to the existing version of the Gavrilović model. These parameters are:

- Average annual temperature T_0
- Average annual precipitation P_a and
- Soil protection coefficient X_a.

Instead, Average seasonal temperature $T_{0.s}$, Average seasonal precipitation $P_{a.s}$ and Soil protection coefficient $X_{a.s}$ representing season soil cover are used. Average seasonal temperature $T_{0.s}$ is, as explained in chapter 6, derived based on the calculated change in average values from past to present and later integrated into the temperature maps representing four different seasons, obtained from DHMZ for the past time seasons (1961-1990) in order to produce seasonal $T_{0.s}$ maps for the present time. The same procedure was used to obtain average seasonal precipitation $P_{a.s}$ maps. The soil protection coefficient $X_{a.s}$ is based on landsat 8 data from January 2016, April 2014, August 2013 and October 2014 representing in the same order winter, spring, summer and autumn. The ideal would be if all data (Landsat images) could have come from the same year but due to a large amount of lower quality data, with large amount of clouds, missing data in stipes etc. the chosen dates were selected as the most appropriate and the closest in time to all having good quality data. These maps were explained in more detail in chapter 6.

From these three parameters, only soil protection coefficient affects all three model outputs while average seasonal temperature and precipitation affect only total seasonal volume of the detached soil $W_{a.s}$ and actual sediment yield $G_{y.s}$. Although, when changing the soil protection coefficient based on different land cover maps, each representing one season, the value range of the model output erosion coefficient Z_s is not changed but the spatial distribution of its values is, which can be seen in Figure 43 and 44.

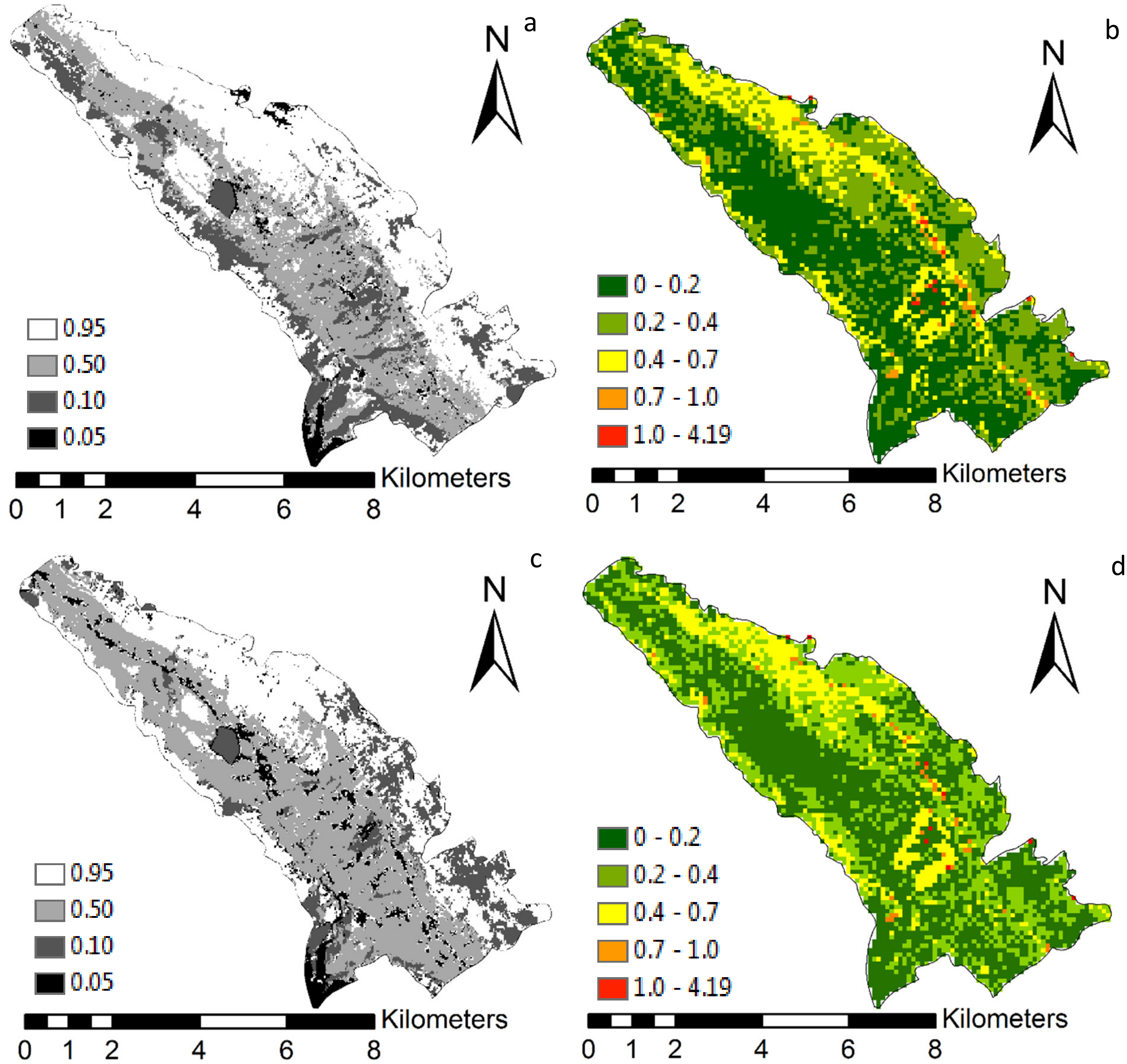


Figure 43: The influence of soil protection coefficient $X_{a.s}$ to erosion coefficient Z_s (a) $X_{a.s}$ winter, (b) Z_s winter, (c) $X_{a.s}$ spring, (d) Z_s spring,

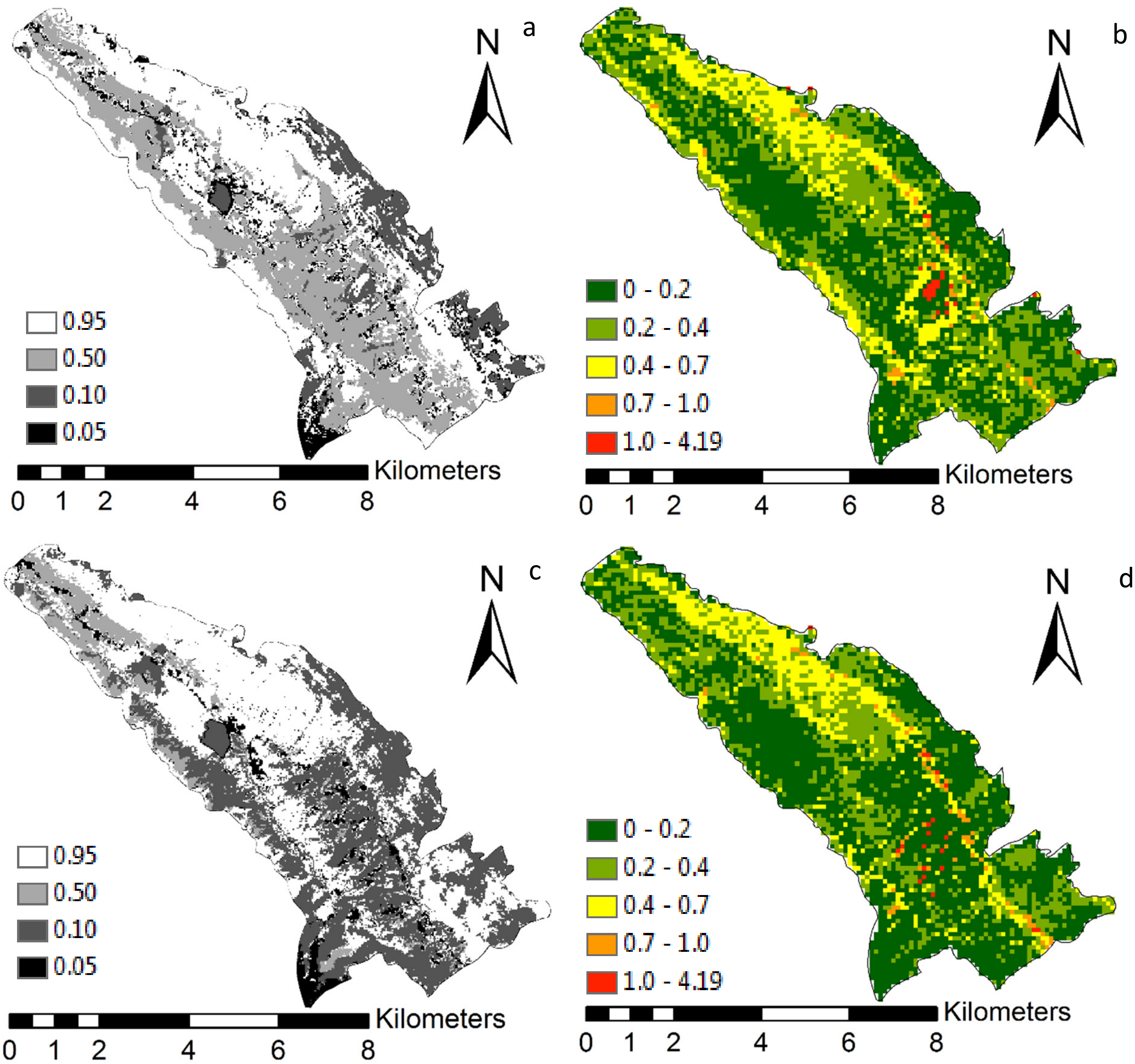


Figure 44: The influence of soil protection coefficient $X_{a.s}$ to erosion coefficient Z_s (a) $X_{a.s}$ summer, (b) Z_s summer, (c) $X_{a.s}$ autumn, (d) Z_s autumn

The mean values for erosion (Table 31) coefficient indicate that the catchment should be the most exposed to erosion processes during the summer (0.25) and winter (0.24) while less during the spring (0.22) and autumn (0.2). This is not actually the case since for the derivation of the erosion coefficient not all significant factor influencing erosion such as temperature and precipitation, as shown in chapter 8, are taken into account. So in reality, the higher values for erosion coefficient indicate the soil type characteristic and vegetation cover effectiveness to protect the top soil surface in a given time of the year. That corresponds to the change in land cover in time cycle of one year, where during the winter and summer vegetation cover is in its decrease and less dense, while during the spring the vegetation is in its peak.

The descriptive statistics, including minimum, mean, maximum values and standard deviation, were given for all three model outputs $Z_s, W_{a.s}$ and $G_{y.s}$ for each season (winter, spring, summer and autumn), with sum of all cell values given only for $W_{a.s}$ and $G_{y.s}$, in Table 31.

Table 31: Descriptive statistics obtained with Gavrilović model and representing model outputs

Season	Statistical parameter	Z_s [-]	$W_{a.s}$ [m^3/cell/season]**	$G_{y.s}$ [m^3/cell/season]**
Winter	Minimum	0.0009	0.008	0
	Mean	0.243	2.31	0.16
	Maximum	4.189	42.25	3.58
	Sum*	/	9908.05	702.55
	Standard deviation	0.213	2.0	0.25
Spring	Minimum	0.0009	0.009	0
	Mean	0.226	2.65	0.20
	Maximum	4.189	54.01	3.10
	Sum*	/	11351.9	854.33
	Standard deviation	0.204	2.50	0.30
Summer	Minimum	0.0009	0.011	0
	Mean	0.250	3.50	0.29
	Maximum	4.189	65.22	5.20
	Sum*	/	14989.94	1233.13
	Standard deviation	0.219	3.17	0.44
Autumn	Minimum	0.0009	0.019	0
	Mean	0.204	4.64	0.35
	Maximum	4.189	99.13	7.29
	Sum*	/	19902.23	1513.70
	Standard deviation	0.204	4.67	0.65

*[m^3/catchment/season]
** cell size is 100x100m or 0.01 km^2

From a given Table 31 and Figure 45 can be seen the distribution of soil loss in different time of a year. Autumn is the biggest contributor to soil loss in a year, followed by summer, spring and at last winter. Since temperature and precipitation have a significant influence on soil loss and Gavrilović model their influence is seen in the obtain values for each season. The time of the year with the most rain in Dubračina catchment is autumn (517.3 mm for present time), followed by winter, spring and summer. The high values of soil loss in summer are a result of high temperature in contribution to rainfall. The lowest values for soil loss are obtained for winter period which is as expected due to lower temperature and precipitation.

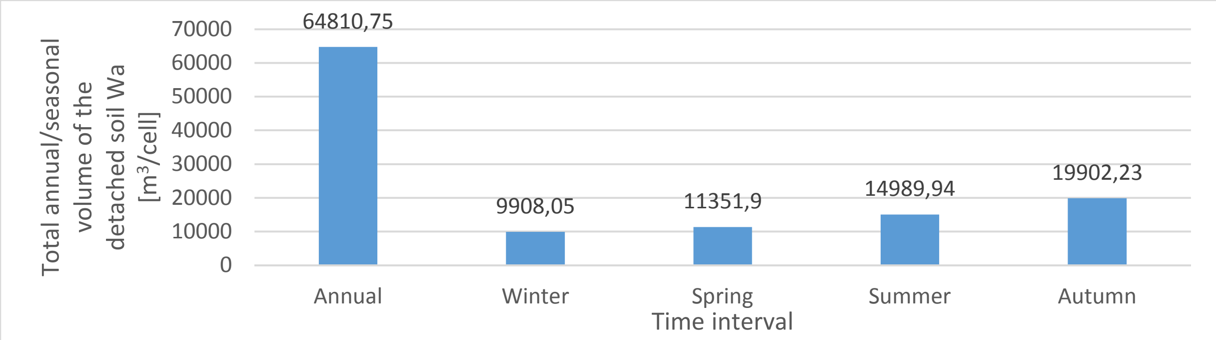


Figure 45: Redistribution of the soil loss within the seasons and comparison with annual soil loss for present time

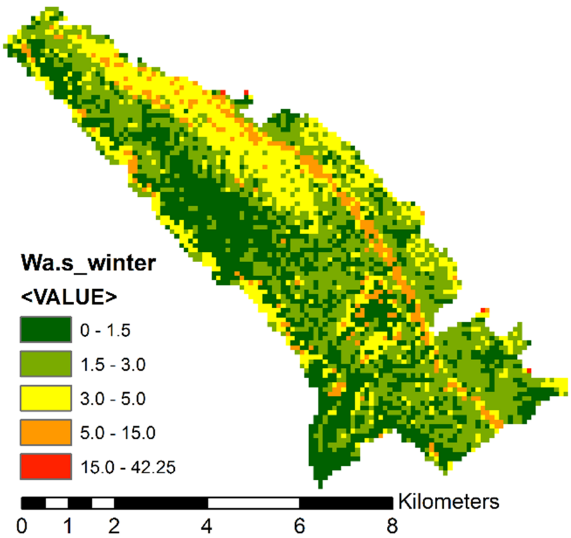
When comparing the values obtained from chapter 9.1 presenting annual values for W_a for the present time and ones showed here representing seasonal values $W_{a.s}$ it can be noted that the overall sum of values obtained for season (56 152.23 m^3/catchment/year) is approximately 13% less than one obtain for the entire year (64 810.75 m^3/catchment/year). It does not match the derived annual production entire but it is a good approximation of its values. The biggest influence on this change has vegetation cover or land cover. It should be noted that since it was not possible to obtain the Landsat images for all season from the same year an error in land cover maps deriving from that is the biggest contributor to the difference in obtained values. Since the temperature and precipitation are averaged values representing season but still proportionally distributed within the year they are considered to have lesser impact upon obtained difference in derived values for soil loss in the catchment.

In the Table 32 average values for all three model outputs for each season is given for Dubračina sub-catchments as well as derived maps for Total seasonal values for the detached soil W_a and Actual sediment yield G_y.

Table 32: Seasonal model outputs obtained from Gavrilović model for all tributaries

Tributary	$Z_{s\ mean}$ [-]				$W_{a.s\ mean}$ [m^3/cell/season]				$G_{y.s\ mean}$ [m^3/cell/season]			
	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn
Duboki	0.30	0.28	0.30	0.29	2.93	3.31	4.22	6.51	0.23	0.27	0.33	6.51
Bronac	0.28	0.27	0.27	0.30	2.75	3.21	3.86	6.60	0.21	0.27	0.32	6.60
Cigančica	0.29	0.29	0.29	0.31	2.85	3.32	4.02	6.89	0.20	0.24	0.32	6.89
Leskovnik	0.38	0.37	0.39	0.38	3.78	4.61	5.70	8.71	0.09	0.09	0.15	8.71
Sušik	0.32	0.31	0.33	0.35	3.14	3.96	4.95	8.16	0.09	0.10	0.16	8.15
Ričina Tribaljska	0.26	0.21	0.22	0.19	2.52	2.64	3.17	4.43	0.07	0.09	0.12	4.43
Slani Potok	0.33	0.29	0.32	0.21	3.08	3.25	4.24	4.68	0.33	0.37	0.59	4.68
Mala Dubračina	0.31	0.27	0.28	0.19	2.82	2.94	3.62	4.09	0.35	0.45	0.58	4.08
Kučina	0.22	0.17	0.20	0.14	2.01	1.99	2.83	3.21	0.08	0.11	0.16	3.21
Mužinići	0.24	0.19	0.18	0.14	2.32	2.27	2.51	3.27	0.13	0.15	0.20	3.27
Malenica	0.22	0.20	0.24	0.18	1.97	2.33	3.30	4.15	0.09	0.12	0.20	4.15
Kostelj	0.19	0.19	0.21	0.15	1.77	2.00	2.75	3.30	0.22	0.25	0.34	3.29

The change in the spatial distribution of Total seasonal values for the detached soil $W_{a.s}$ can be seen in Figure 46, where the soil loss in autumn is considerably higher than in winter. Similar change can be noted for Actual sediment yield shown in Figure 46.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3.0 - 5.0
5.0 - 15.0
15.0 - 42.25
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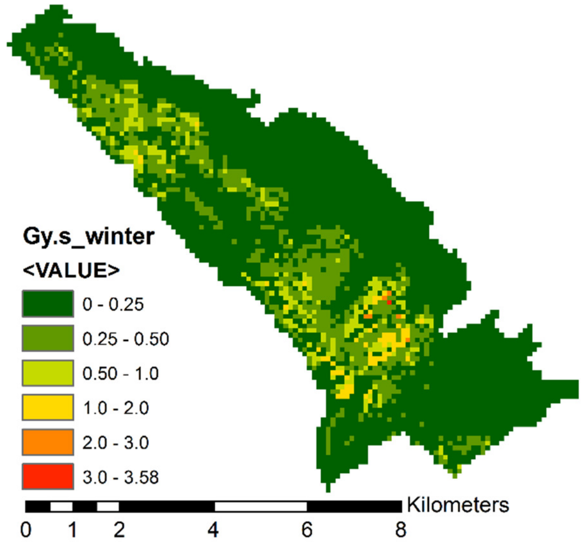
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2.0 - 3.0
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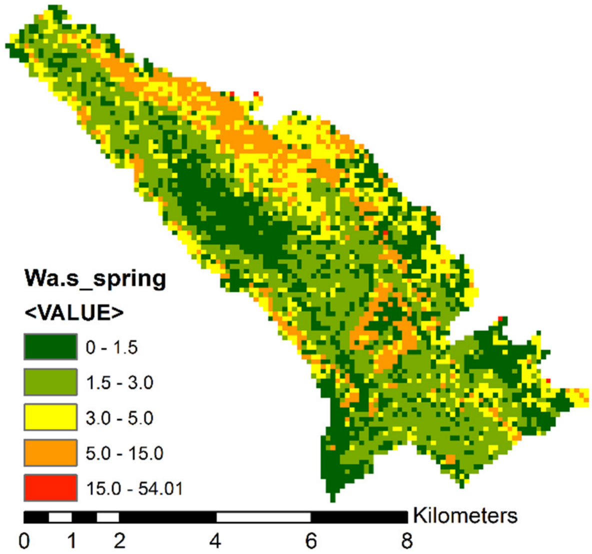
Kilometers
0 1 2 4 6 8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3.0 - 5.0
5.0 - 15.0
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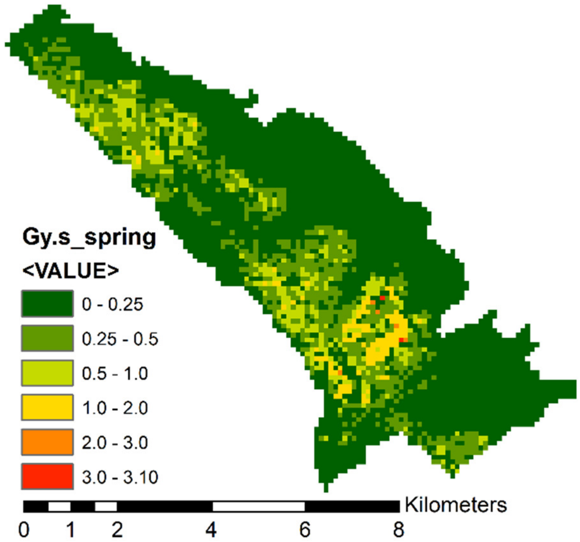
Kilometers
0 1 2 4 6 8


Gy.s_spring
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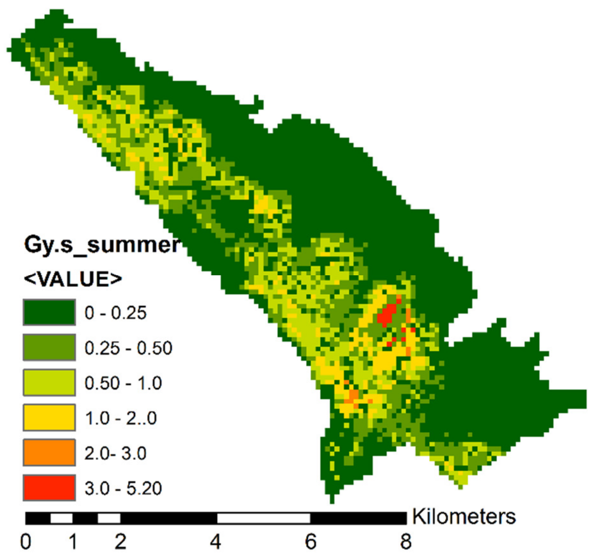
0.25 - 0.5
0.5 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 3.10
Kilometers
0 1 2 4 6 8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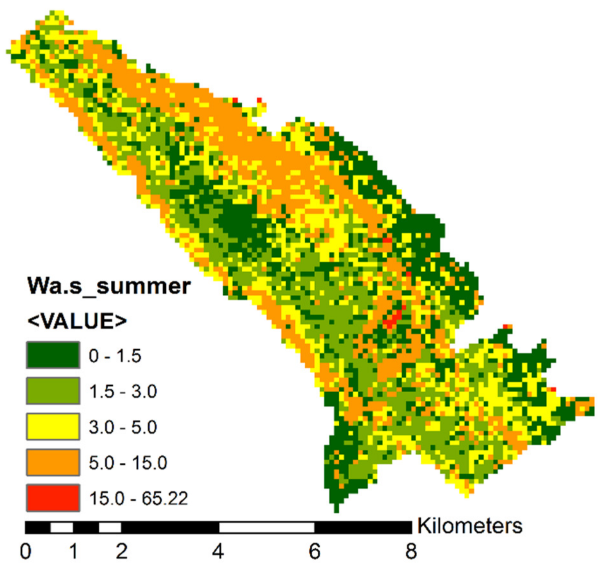
1.0 - 2..0
2.0- 3.0
3.0 - 5.20
Kilometers
0 1 2 4 6 8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1.5 - 3.0
3.0 - 5.0
5.0 - 15.0
15.0 - 65.22
Kilometers
0 1 2 4 6 8

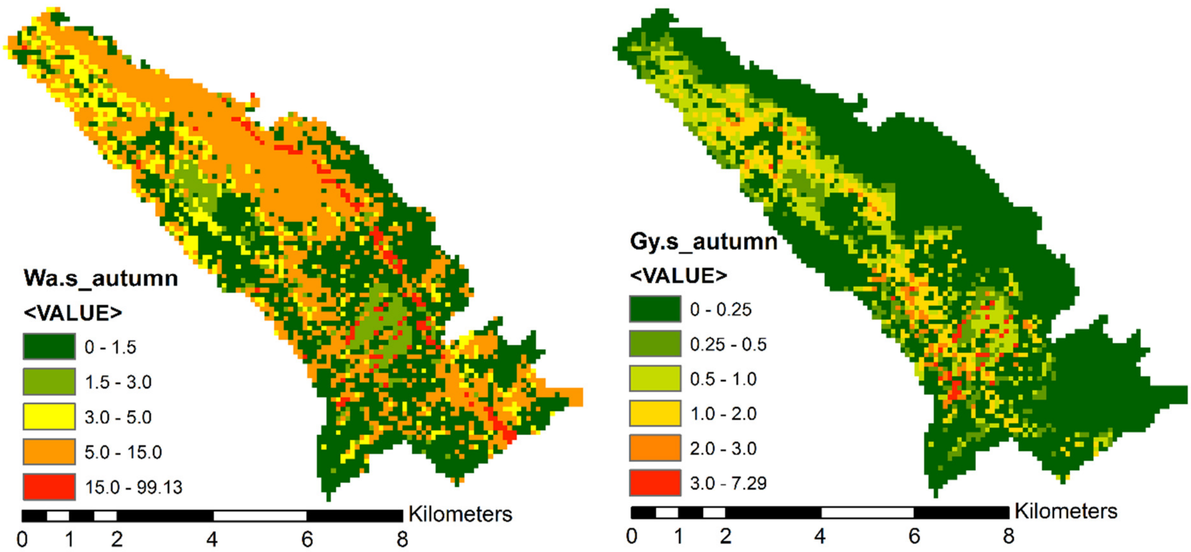


Figure 46: Season model output for Total seasonal volume of the detached soil $W_{a.s}$ and Actual sediment yield $G_{y.s}$ expressed in m^3/cell/season

CHAPTER 10: EROSION MODEL VERIFICATION

Erosion can occur in many forms, from gullies, mass movement of soil or landslides to flood erosion, sheet erosion to stream channel erosion, with eroded sediment transportation and deposition. Each of these events is the consequence of the previous one which is one of the reasons that makes erosion measurement hard (Griesbach et al., 1997). Morgan (2005) stated: "Measurements are subject to error. Since no single measurement of soil loss can be considered as the absolutely correct value, it is virtually impossible to quantify errors".

Data on soil erosion production and its controlling factors can be measured on field or in a laboratory under simulated conditions, but the data obtained from field measurements are considered the most reliable. To measure data on the field is not always an easy task due to the time and space changing environmental and climate conditions, which makes harder to define the main causes of erosion and understanding of its processes in an area of interest (Morgan, 2005).

According to Griesbach et al. (1997) "in contrast with other main hydrological variables such as rainfall, streamflow, snow, etc., the erosion sequence is a one-way process in the human time scale and thus cannot produce two similar events since sediment material sources, once eroded are not renewable".

There are many measurement techniques that can be used to monitor and measure surface erosion some of which are applied in the Dubračina catchment and will be addressed in this chapter. For every erosion affected area the assessment of the erosion intensity and sediment production as well as monitoring and measurement of its on-site values are required. Both assessment and monitoring was defined by Pellant et al. (2005) where:

"Assessment is the process of estimating or judging the value or functional status of ecological processes in a location at a moment in time (Pellant et al., 2005)."

"Monitoring is the orderly collection, analysis, and interpretation of resource data to evaluate progress toward meeting management objectives (Pellant et al., 2005)."

In the next section of this Chapter applied erosion monitoring methods on the Dubračina catchment are discussed and its results presented.

10.1 Erosion observation on Dubračina catchment

When selecting the observation method various different factors needs to be taken into consideration, such as: (i) the amount of accuracy and precision needed, (ii) the financial cost of monitoring, (iii) time requirement for its conduction, (iv) availability of qualified staff assigned for monitoring, equipment needed, etc. (Ypsilantis, 2011).

The most appropriate observation method was chosen for the implementation on the Dubračina catchment where financial cost, needed crew, land accessibility and ownership, equipment requirements and many more factors were considered in the process of their selection.

10.1.1 Verification of Landsat derived land cover map for present time

"Remote sensing is the sensing of the Earth`s surface from space by making use of the properties of electromagnetic waves emitted, reflected or diffracted by the sensed objects, for the purpose of improving natural resources management, land use and the protection of the environment" (United Nations, 1986). In the context of erosion monitoring, this method includes data collected from the ground, aircraft, or satellites, including ground-based and aerial photographs and satellite imagery (Ypsilantis, 2011). One of the appropriate remote sensing data that can be used for land cover monitoring is multispectral imagery taken from a satellite (e.g. Landsat) and can be obtained from different archives (such as from USGS Global Visualization Viewer). Images obtain from such information sources can be used on a regional scale or a more detailed scale to determine land cover in the area of interest using an appropriate software (e.g. ERDAS Imagine) for data training using high-resolution multispectral imagery. This monitoring method was used to obtain land cover categories on the Dubračina catchment, where the source of the information was USGS Glovis archive and the software used for land classification was ERDAS Imagine 14.0. More detailed explanation of its derivation is given in the Chapter 6. Obtained land cover classification was additionally verified for the present time and summer season (August 2013) using visual land survey method and observing twenty (20) on site locations in July 2016. On each location (Figure 47) GPS coordinates were noted, as well as photograph documentation of the site and descriptive observation of vegetation cover (Table 33). The observation was made in July 2016 so to correspond the same year period for which land cover for present time was made (August

2013). For each location observations notes were compared in ERDAS Imagine software to land cover category derived from Landsat data. Observation locations and its results are presented in Table 33.

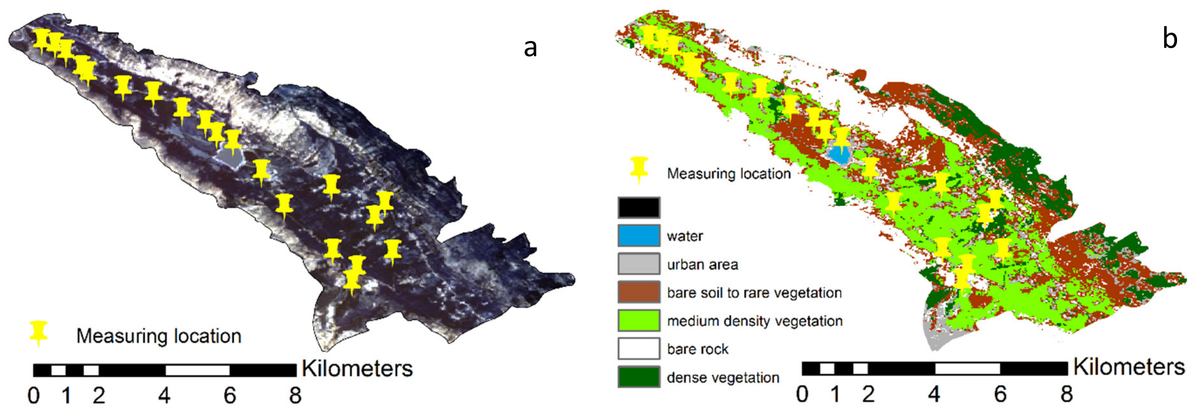


Figure 47: (a) Measuring location points in the Dubračina catchment; (b) Measuring points on land cover representing present time and summer season from 6.8.2013

The observed vegetation cover on chosen location corresponded well with ones obtained with Landsat 8 image land cover classification. On all surveyed locations vegetation cover or land cover corresponds to one obtained with ERDAS Imagine software and Landsat 8 images. Smaller errors were noted in locations 9, 10, 11, 12 and 16 when comparing the locations close surroundings. These errors refer to replacing smaller parts of urban areas with bare rock category obtained with Landsat 8 in locations 10, 11, 12 and 16. In location 9 urban area was derived from Landsat images while the bare soil to rare vegetation is observed directly on filed survey.

Table 33: On field observation locations and vegetation cover/land cover category comparison

Observation point N^0	Longitude	Latitude	Observed vegetation cover	Landsat land cover category
1	14.617047	45.256260	***On location:*** Dense vegetation prevails. ***Close surroundings:*** below the road meadow and medium density vegetation	***On location:*** Dense vegetation ***Close surroundings:*** bare soil to rare vegetation and medium density vegetation
2	14.620763	45.255129	***On location:*** Medium density vegetation ***Close surroundings:*** Medium density vegetation with small parts of meadow and rare urban area	***On location:*** Medium density vegetation ***Close surroundings:*** bare soil to rare vegetation and medium density vegetation, urban area
3	14.623636	45.253210	***On location:*** Rare vegetation ***Close surroundings:*** Upper steep parts of catchment visible – bare rock partially rare vegetation, close by rare urban area	***On location:*** Bare soil to rare vegetation ***Close surroundings:*** Upper part of the catchment bare rock to bare soil to rare vegetation, urban area in a close location surrounding
4	14.627808	45.248859	***On location:*** medium density vegetation ***Close surroundings:*** Urban area	***On location:*** Medium density vegetation ***Close surroundings:*** urban area
5	14.630030	45.247128	***On location:*** Medium density vegetation ***Close surroundings:*** Partially rare vegetation within medium density vegetation. Urban area in its close surroundings. Upper steep parts of catchment visible – bare rock partially rare vegetation	***On location:*** Medium density vegetation ***Close surroundings:*** Smaller area with bare soil to rare vegetation and urban area close by. Upper part of the catchment bare rock to bare soil to rare vegetation.
6	14.639420	45.243460	***On location:*** Medium density vegetation ***Close surroundings:*** Rare urban area	***On location:*** Medium density vegetation ***Close surroundings:*** Urban area
7	14.647677	45.241608	***On location:*** Urban area ***Close surroundings:*** Medium dense vegetation with partially rare vegetation	***On location:*** Urban area ***Close surroundings:*** Medium density vegetation, smaller area with bare soil to rare vegetation
8	14.656109	45.237249	***On location:*** Bare soil	***On location:*** Bare soil to rare vegetation

			Close surroundings: Bare rock partially, lower parts with medium density vegetation and partially rare vegetation and meadow. Upper steep parts of catchment visible – bare rock	***Close surroundings:*** Smaller areas with Bare rock, bare soil to rare vegetation and medium density vegetation. Upper part of the catchment bare rock
9	14.661799	45.233687	***On location:*** Rare vegetation to bare soil partially ***Close surroundings:*** Rare to medium density vegetation. Upper steep parts of catchment visible – bare rock	***On location:*** Bare soil to rare vegetation ***Close surroundings:*** Bare soil to rare vegetation, medium density vegetation and partial urban area. Upper part of the catchment bare rock.
10	14.665060	45.230546	***On location:*** Rare vegetation ***Close surroundings:*** Urban area. Upper steep parts of catchment visible – bare rock	***On location:*** Bare soil to rare vegetation ***Close surroundings:*** Bare rock to urban area. Upper part of the catchment bare rock.
11	14.669548	45.228518	***On location:*** lake ***Close surroundings:*** Urban area	***On location:*** *Water* ***Close surroundings:*** Urban area and small parts of bare rock
12	14.677426	45.220309	***On location:*** Urban area ***Close surroundings:*** Rare vegetation	***On location:*** Urban area ***Close surroundings:*** Urban area and small parts of bare rock
13	14.682978	45.211081	***On location:*** Medium density vegetation ***Close surroundings:*** Rare urban area, Rare to medium density vegetation	***On location:*** Medium density vegetation ***Close surroundings:*** Bare soil to rare vegetation, urban area and medium density vegetation
14	14.702010	45.189780	***On location:*** Bare rock ***Close surroundings:*** Bare rock to rare vegetation, rare urban area	***On location:*** Bare rock ***Close surroundings:*** Bare rock to rare vegetation, smaller urban areas
15	14.703040	45.193659	***On location:*** Medium density vegetation ***Close surroundings:*** Urban area, medium density vegetation to dense vegetation. Visible lower part of catchment with bare rock to rare vegetation	***On location:*** Medium density vegetation ***Close surroundings:*** Urban area, bare soil to rare vegetation with parts of bare rock
16	14.713250	45.198127	***On location:*** Dense vegetation	***On location:*** Dense vegetation

			Close surroundings: Visible only close range dense vegetation. Up on the road urban area	***Close surroundings:*** Urban area and bare rock
17	14.711116	45.211073	***On location:*** Dense vegetation ***Close surroundings:*** Dense vegetation	***On location:*** Dense vegetation ***Close surroundings:*** Dense vegetation
18	14.707866	45.207751	***On location:*** Bare rock, bare soil ***Close surroundings:*** Bare rock and bare soil	***On location:*** Bare rock and bare soil ***Close surroundings:*** Bare rock and bare soil
19	14.696372	45.216285	***On location:*** Medium density vegetation ***Close surroundings:*** Medium density to dense vegetation, rare urban	***On location:*** Medium dense vegetation ***Close surroundings:*** Medium dense vegetation, dense vegetation, rare urban and bare soil in its surroundings
20	14.696946	45.198502	***On location:*** Medium density vegetation ***Close surroundings:*** Rare to medium density vegetation, small urban area	***On location:*** Medium density vegetation ***Close surroundings:*** Medium density vegetation, rare vegetation with small urban area

10.1.2 Verification of erosion coefficient (intensity) map

According to Ypsilantis (2011) the relative degree of erosion can be estimated by observing certain visual signs, such as, gully's, flow paths, depositions, etc. and these monitoring method can provide a qualitative assessment of erosion. This method of erosion monitoring is used from the 1970s until today and provides relatively quick estimation of erosion processes (erosion intensity) in the catchments, it enables multiple observations during one field survey and the identification of the potential erosion problems on the catchment. This method was used for the observation of the erosion processes representing erosion intensity in the catchment on 20 different locations (Figure 48) for which GPS coordinates were noted as well as any visual signs of erosion processes, presence of soil loss, gully formation, sediment deposition on the site or in the river bed, etc. The notes were then compared with erosion coefficient values that define erosion intensity categorisation on each chosen location (Table 34).

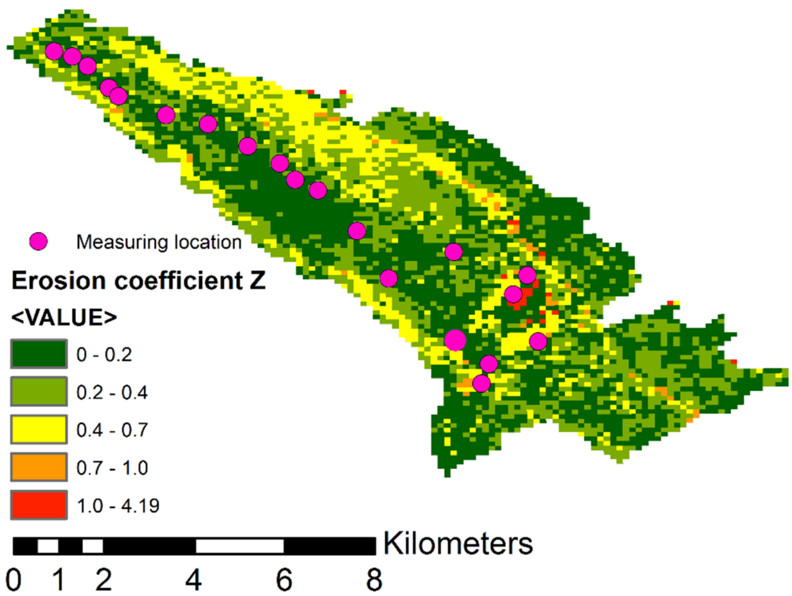


Figure 48: Erosion coefficient for the present time series and locations chosen for field survey

Very good results were obtained from the comparison of field survey and erosion coefficient obtained with the Gavrilović model for the present time series. Most of the observed points (eleven (11)) correspond to very slight erosion, six (6) points to slight erosion, and one point for each category representing medium, severe and excessive erosion.

Table 34: Visual signs of erosion processes in the catchment obtained by visual survey and its comparison to erosion coefficient model output

Observation location N^0	Longitude	Latitude	Visual signs of erosion processes, soil loss, gullies, sediment deposition on the site and/or in the water bed	Erosion coefficient Z
1	14.617047	45.256260	No signs of erosion	0.01
2	14.620763	45.255129	Small signs of erosion, angled trees	0.23
3	14.623636	45.253210	Small signs of erosion	0.23
4	14.627808	45.248859	No signs of erosion	0.17
5	14.630030	45.247128	Signs of erosion, some sediment	0.23
6	14.639420	45.243460	No signs of erosion	0.22
7	14.647677	45.241608	Sediment detained in the river bed	0.16
8	14.656109	45.237249	Signs of erosion, upper part sediment detention	0.34
9	14.661799	45.233687	Sediment detention	0.26
10	14.665060	45.230546	No signs of erosion	0.12
11	14.669548	45.228518	No signs of erosion	0.01
12	14.677426	45.220309	No signs of erosion	0.15
13	14.682978	45.211081	Sediment detention in river bed	0.04
14	14.702010	45.189780	Signs of erosion, angled trees, sediment detention, sediment in the river bed	0.75
15	14.703040	45.193659	Sediment in the river bed	0.05
16	14.713250	45.198127	No signs of erosion	0.18
17	14.711116	45.211073	Sings of erosion, sediment detention, road damages	0.63
18	14.707866	45.207751	Signs of excessive erosion, gullies, soil detachment, visible erosion processes, angled trees	1.17
19	14.696372	45.216285	No signs of erosion	0.16
20	14.696946	45.198502	Sediment in the river bed	0.12

In some point were the erosion coefficient was found to correspond to very slight to slight erosion, some sediment yield were noted within the river beds. These sediments are the result of erosion processes in the upper part of the sub-catchments and not the location itself. Some indications of erosion processes noted in the field are shown in the Figure 49.

Figure 49: Visual signs of erosion processes captured in field survey in June 2016 (pictures taken by author in July, 2016)

10.1.3 Investigation location – upper part of Slani Potok sub-catchment – surface soil loss verification

The chosen location for the verification of surface soil changes is located on the upper part of the Slani Potok sub-catchment (Figure 50).

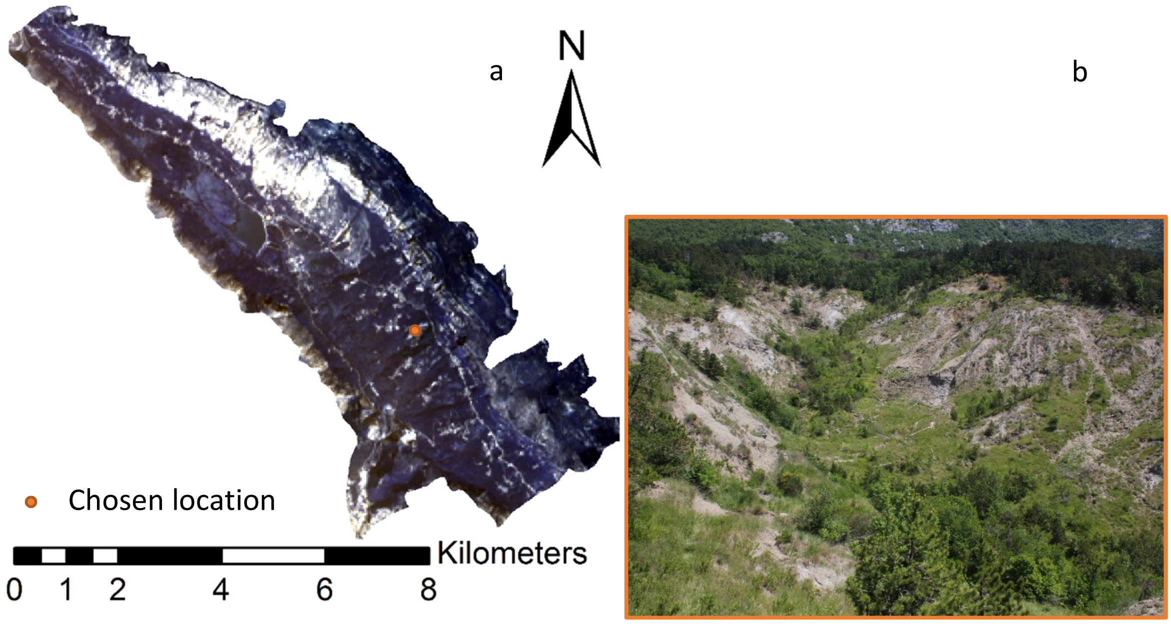


Figure 50: Chosen location for surface soil loss measuring (a) the location in the Dubračina catchment, (b) taken photograph of the location in June 2014

The location is characterized by excessive erosion processes (erosion coefficient values larger than 1.0) and it is the most exposed area to water erosion in the entire catchment. The estimated annual soil loss production with Gavrilović model in this location is 66.2 m^3/cell/year. The indication of erosion processes intensity and the proportion of the change can be seen even with only visual comparison of the site presented in Figures 51-53, each taken with 1 year time delay, starting in June 2014 and ending in July 2016.

The change in the soil surface in noticeable by visual observation and it shows the two year change in the area affected by excessive erosion in the Slani Potok sub-catchment, where the images were taken with one year delay. First image was taken in June 2014 (Figure 51) and followed by the second in June 2015 (Figure 52) and July 2016 (Figure 53). The changes between each year are significant, as seen in Figures 51-53 and the soil surface change substantial. On the first image representing June 2014 the area observed is bare soil partially covered with vegetation mainly grass and low shrubs. The image taken in June 2015 shows the one year change in soil surface and cover. It can be noted that the area covered with bare soil has increased significantly and the area covered with vegetation has decreased. Also the changes in soil surface and topography is evident, mostly in areas now covered only with bare soil. These changes are even more evident in images taken in July 2016.

Figure 51: Location used for close range photogrammetry measurement method (photograph taken by author in June, 2014)

Figure 52: Location used for close range photogrammetry measurement method (photograph taken by author in June, 2015)

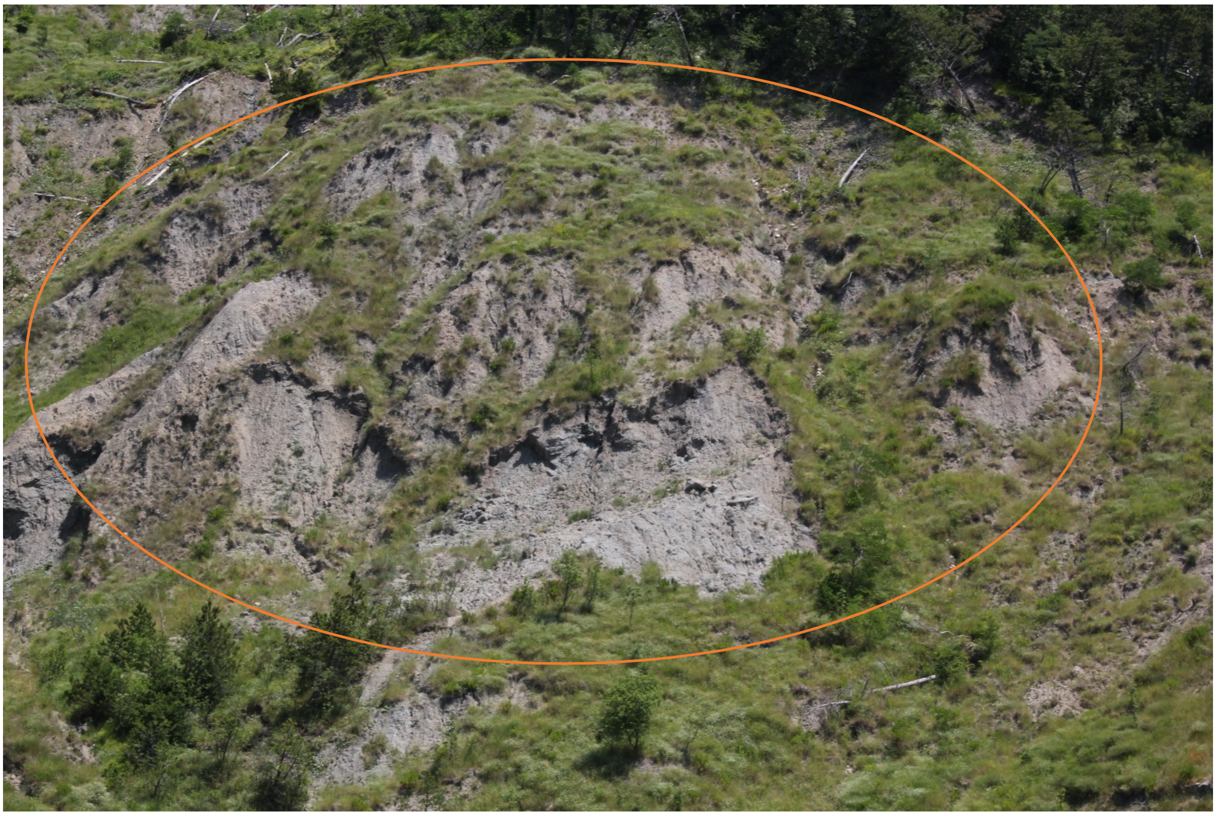


Figure 53: The same site taken from a different location in the July 2016 (photograph taken by author)

It should be noted that this is only one small segment of the area affected by excessive erosion and only the indication of the proportion of soil surface changes in this area.

10.1.4 Investigation location – Malenica tributary –sediment detention in the riverbed

The detained sediment was observed in the Malenica tributary (Figure 54). The measurement has begun in June 2014 and ended in July 2016. During the measurement period sediment yield was taken out of the riverbed twice, first in November 2014 and in June 2016 for the second time.

Previous research has shown that measurements of actual sediment yield or erosion sediment transported through river network that the value for this parameter can vary from 20 to 90% in very small catchments (e.g. 2 km^2) and from 3 to 15% in catchments ranging from 100 to 1000km^2 (Griesbach et al., 1997).

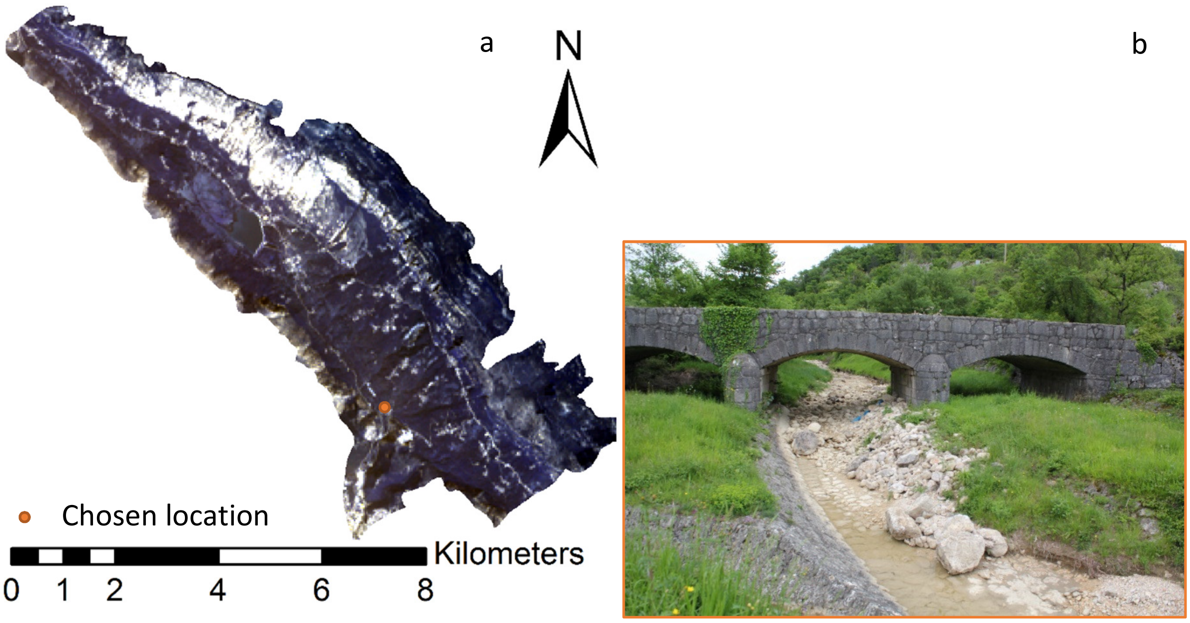


Figure 54: (a) The chosen location for sediment yield measurement within the Dubračina catchment; b) the photograph of the measurement location – tributary Malenica

The visual comparison of the river bed in different time interval was made and the changes in it were recorded as images. The visual comparison of the riverbed using images from before and after cleaning the sediment yield are shown in Figure 55.

From this images it is clearly visible the large amount of sediment detained in the river bed. After the first cleaning of the riverbed in November 2014 the sediment detention has shown to increase form month to month (research arhive) and after a year and a half the considerable amount of sediment in a regulated river bed was detained again. This sediment does not include the sediment transported downstream in the lower parts or catchment but only the one that has remained.

Figure 55: Photo of the location (a) October 2014; (b) November 2014, (c) June 2015 and (d) July 2016 (photograph taken by author)

10.2 Recommendation for future monitoring and measurements

It is recommended that soil erosion monitoring and data collection should be conducted in a continuous 3-year time period (Ypsilantis, 2011). So, on Dubračina catchment, the monitoring including visual observation method needs to be continued in the future. The monitoring of the seasonal land cover changes in the catchment itself needs to be observed and noted. The measuring erosion sediment yield needs to be conducted and the preparation work for that continued. The most attention needs to be given to location of erosion sediment measurement. The primary location in the upper area of Slani potok affected with excessive erosion has shown to be challenging due to poor accessibility, difficult conditions for equipment setting, occasional local landslides affecting measurements etc. For this reason, and learning from the observations made in the last two years, the special attention will need to be given on appropriate measurement location taking into consideration its accessibility, equipment setting and method selection. One of the methods that can be easily conducted is Close range photogrammetry. This method is used for capturing detailed information about erosion on various size plots, from 1m^2 to the entire hillslope. For its implementation a quality and calibrated camera needs to be used for capturing x, y, z coordinate data in a series overlapping photographs that are taken from the investigated plot. Within the research plot one or more fixed points are recommended to be placed. For larger size plots, three or four reference elevation points are needed. Each reference point consist of bedrock or rebar driven deep enough in the ground to remain stable. The rebar location is recorded (x, y, z coordinates) with GPS device. Furthermore, information obtain from GPS device and a series of recorded pictures from the investigation plot, need to be processed with a sophisticated software (such as PhotoModeler Scanner or Kuraves). Mentioned software is then used to create digital terrain model that consists of a closely spaced grid with thousands of x,y,z data points. Taking on site pictures in chosen time intervals can provide the information about the change in the terrain surface due to erosion processes.

CHAPTER 11: EROSION MITIGATION MEASURES RECOMMENDATION FOR FUTURE SOIL AND WATER MANAGEMENT IN DUBRAČINA CATCHMENT

There can be many approaches to soil conservation but all need to take into consideration cultivated land, non-cultivated land and urban area (Figure 56).

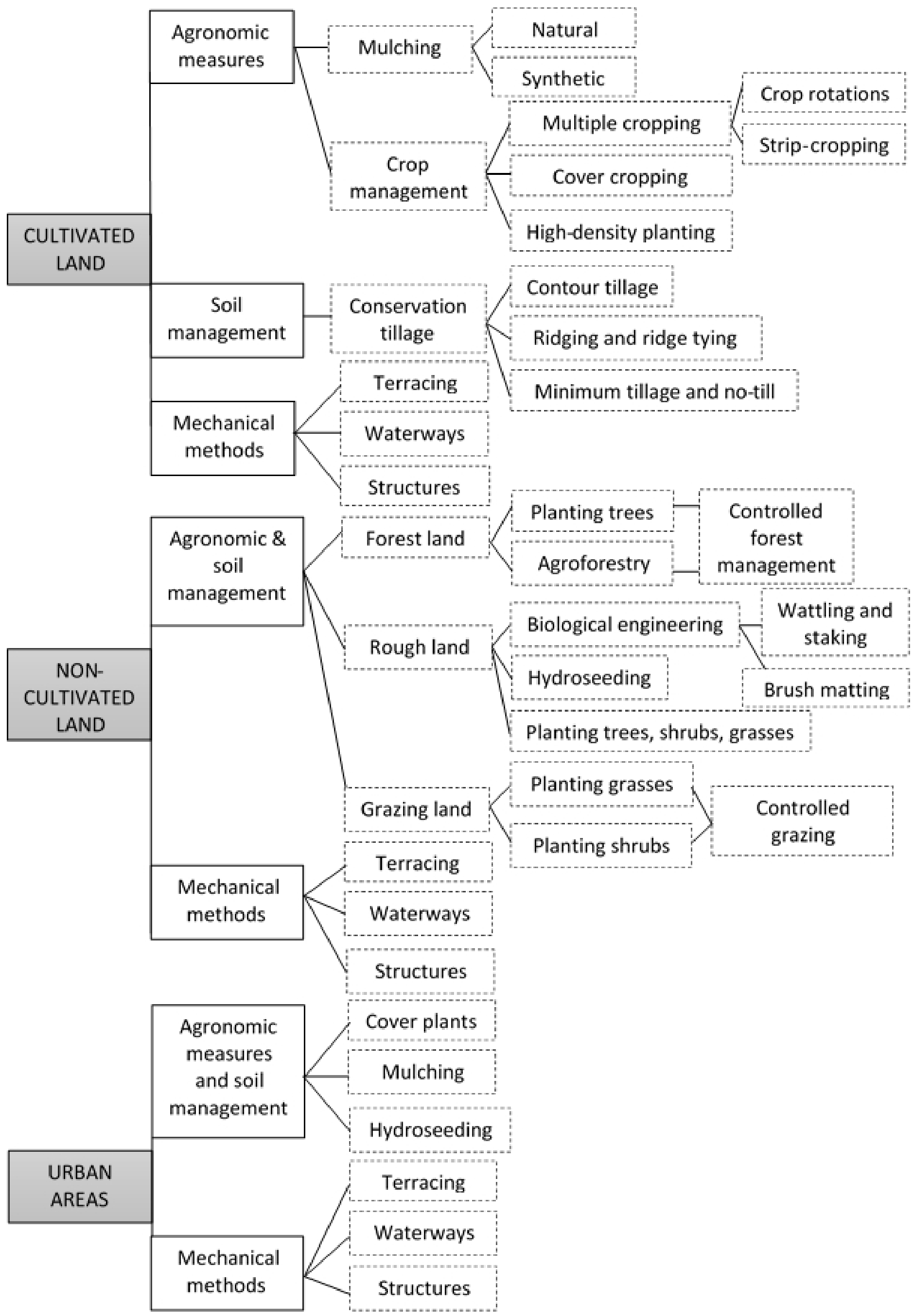


Figure 56: Soil conservation strategies for cultivated, non-cultivated land and urban areas (Morgan, 2005)

The most often used anti-erosion measures are biological erosion control measures and mechanical structures. While biological measures, use the effect of a plant to protect and reduce soil erosion, are less expensive than engineering measures but not always sufficient in erosion control. Such measures include crop rotation, multiple cropping, high density planting, revegetation, etc. Mechanical structures are often used to enhance the performance of applied biological measures and the combination of both type of measures is encouraged today. Engineering structures with erosion control purposes can be permanent (terraces, spillways, culverts, gabions, etc.) or temporary structures (countour bunds, sand bags, silt fences, surface mats, log barriers, etc.) (Morgan, 2005; Blanco and Lal, 2008). The selection of anti-erosion measures depends on many things, from severity of erosion in the area of need, soil type, topography, climate, social, economical and political circumstances.

There are many measures that can be applied on Dubračina catchment with soil erosion mitigation and prevention purposes, but here, only ones related to mitigation of erosion sediment yield in river network and erosion sediment production mitigation and prevention from construction sites will be address since there are recognised to be the most important and till now insufficiently accentuated in the Dubračina catchment. During the years, as described in Chapter 3, there were several project with structural measures propositions, but insufficient financial construction was in most cases the limiting and decisive factor leading to their abandonment and implementation delay for future time. Here, only measures with smaller financial requirements will be addressed with aim for its easier application.

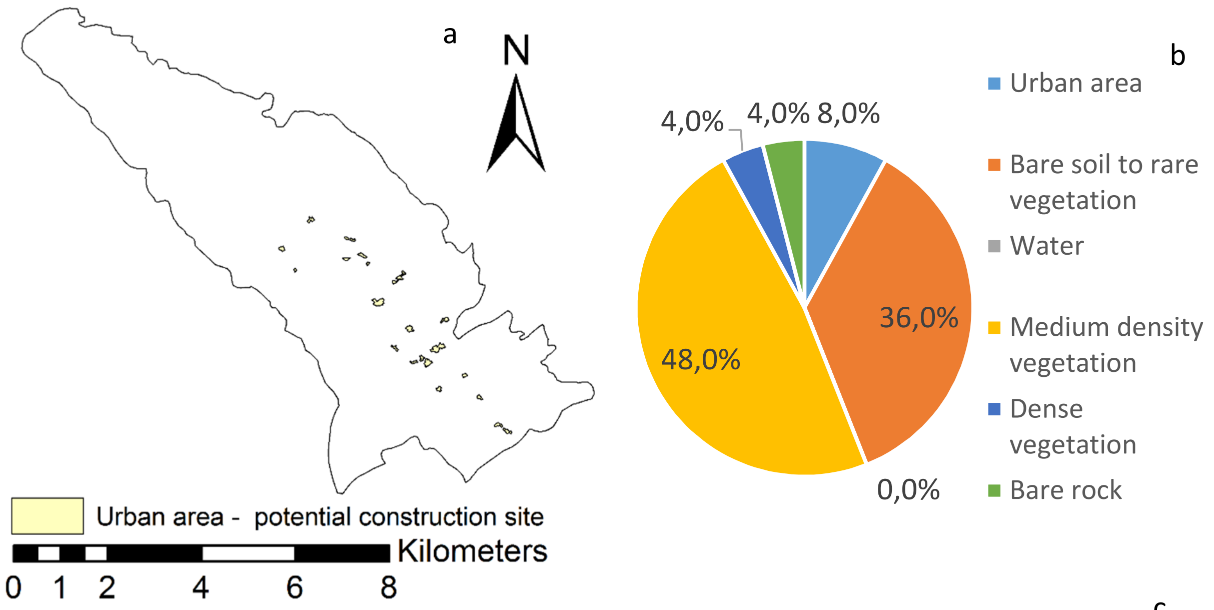
Erosion and water management are closely related and joined when the need for mitigation of soil erosion produced sediment yield transported through river network downstream is needed. Water pollution and decrease in river bed flow capacity are only few of soil erosion consequences. The main mitigation measure should be regular cleaning of river beds in the catchment with emphasis given on seasons with highest sediment production present. During one year time period this measure should be conducted minimum two times in order to be effective, when until today it was conducted up to once a year and sometimes even less. This measure would contribute the most to the tributary Malenica, Slani Potok and Mala Dubračina where such sediment is often present.

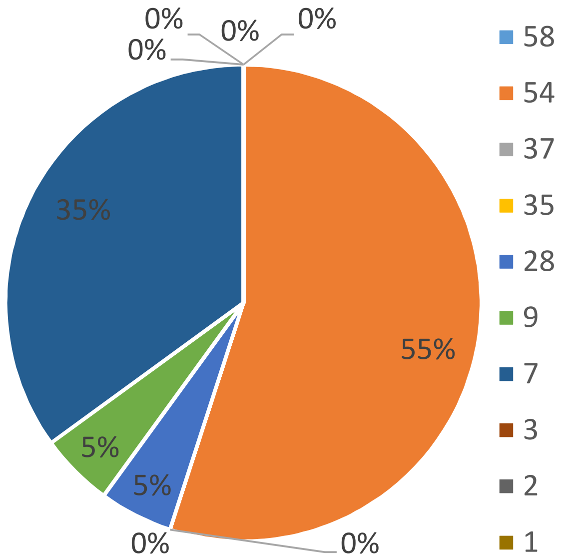
Construction sites has been recognised as a significant source of soil erosion sediment for long time now. In the United States, construction sites larger than 0.02 m^2 are required to apply erosion control measures from 1970`s to today. From 1990`s even smaller areas than 0.02 km^2 are recognised as significant and in need for erosion control measures (http://wi.water.usgs.gov/pubs/fs-109-00/fs-109-00.pdf). Such measures are not foreseen by Croatian legislative framework but should be considered by local government in areas prone to erosion processes.

On Dubračina catchment, twenty different potential construction sites, obtained by local municipality archive and unpublished maps from Spatial Plan of Vinodol Valley (2007), were analysed with a purpose to define potential change in Total annual volume of the detached soil W_a, that would derive from a cell (100x100 m) under construction, and to analyse the need for the application of erosion control measures on construction sites. The spatial distribution and location of these potential construction sites are shown on Figure 56a. The overall 48% of potential construction sites are currently covered with medium density vegetation and 36% with bare soil to rare vegetation, while all other land cover categories are present in smaller percentage (Figure 56b). Only three types of soil are present on these sites (Figure 56c), one being rendzina on marl limestone, rigosol and regosols (50:30:20), the other rendzina on talus, colluvial soil, kalkocambisol and colluvial (60:20:20) and the third rigosol on colluvium and flysch, colluvial soil calcareous, rendzina on colluvium, flysch and talus (60:30:10).

The difference (Table 35) in values for Total annual volume of the detached soil are obtained by changing the “real” values of soil protection coefficient Y on the chosen area to 0.9, which was proposed in Chapter 5, Table 15. The minimum increase (see Table 35) is approximately 23% and occurs on areas with rendzina on marl limestone, rigosol, and regosols (50:30:20) soil type category. The maximum increase, 84.4%, occurs on areas with kalkocambisol, rendzina on dolomite moderately deep and shallow, luvisol (50:30:20) soil type category.

Overall, average values for Total annual volume of the detached soil W_a before the construction is 16.3 m^3/cell/year, and 20.9 m^3/cell/year during the construction, calculated using Gavrilović method with cell size being 100x100m. Notice, that the average increase in sediment production is approximately 28% on an area under construction.





c

Category	Soil type
7	Rendzina on marl Limestone; Rigosol; Regosols (50:30:20)
9	Rendzina on Talus; Colluvial soil; Kalkocambisol, Colluvial (60:20:20)
28	Kalkocambisol; Rendzina on Dolomite Moderately deep and Shallow; Luvisol (50:30:20)
54	Rigosol on Colluvium and Flysch; Colluvial soil Calcareous; Rendzina on Colluvium, Flysch and Talus (60:30:10)

Figure 57: Potential construction sites (a) locations and distribution obtained from local municipality archive, (b) land cover categories in percentage present at potential construction sites, (c) soil type in percentage at potential construction sites with category explanation in table for most important soil type categories present

This increase, by almost 30%, is significant and can cause additional problems on the catchment. Those areas are, along with areas affected with excessive erosion, the most important to consider when planning activities on the catchment and urban development. It is well known fact, that human activities and urban development cause accelerate erosion. In order to mitigate the effect of construction sites on Dubračina catchment prone to soil erosion, it is necessary to apply erosion control measures.

Table 35: Erosion sediment production before and during the construction on potential construction sites and its difference/increase in percentage

No. potential construction site	$W_{a.mean\ before\ construction}$ [m^3/cell/year]*	$W_{a.mean\ during\ construction}$ [m^3/cell/year]*	Increase in W_a
1	13,5	17,1	26,6%
2	9,5	11,8	24,6%
3	25,6	31,5	22,9%
4	11,1	20,9	88,4%
5	11,1	13,6	23,0%
6	15,8	19,5	22,9%
7	17,8	21,9	22,9%
8	29,3	36,5	24,6%
9	8,1	10,1	24,5%
10	5,9	7,3	24,6%
11	29,8	38,3	28,5%
12	22,7	28,1	23,5%
13	23,0	28,7	24,7%
14	5,8	7,2	24,6%
15	10,0	12,3	23,0%
16	15,9	19,8	24,7%
17	16,4	20,1	23,0%
18	16,3	20,3	24,7%
19	29,0	36,2	24,7%
20	9,4	16,9	79,9%
* cell size is 100x100 m			

The most important measure that needs to be applied relates to the retention of the erosion sediment using various methods such as silt fences or burlap rolls and/or many more different and available measures. The most simple to use are silt fences that have been used as erosion control measure for long time. “The silt fence (Figure 57) is installed at the base of the plots with suitable silt fence fabric and wooden or metal stakes to secure the material upright 45 to 76 cm above ground level. The bottom of the sit fence fabric is buried below the ground surface to prevent runoff and sediment from escaping under the silt fence. They allow water to pass through while trapping the sediment” (Ypsilantis, 2011). Low cost in comparison to some other methods, maintenance at different time intervals, small field crow necessities, are some of the advantages of silt fences. It should be noted that if not properly installed, runoff water may undercut the silt fence, leaving them useless afterwards and in need for replacement.

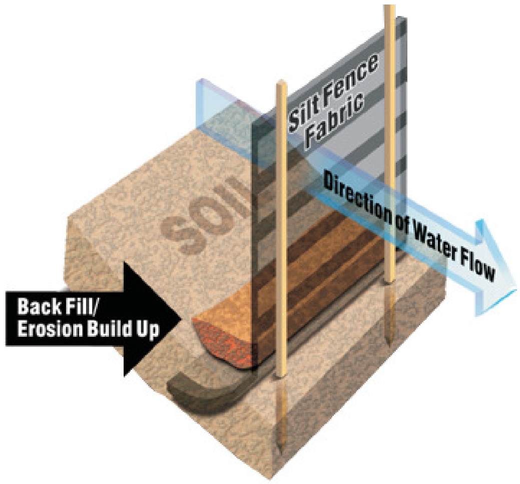


Figure 58: Silt fences (http://www.grip-rite.com/)

This control measure is very easy to apply, relatively economically approachable and easily integrated within local regulations and legislative framework, which is way it is suggested as the most appropriate erosion control measure for construction sites on Dubračina catchment and should be considered in any future spatial planning in the area.

CHAPTER 12: CONCLUSION

Water erosion related problems on Dubračina catchment have been known to exist from 19th century till today. During the years several attempts were made in order to mitigate erosion processes in the catchment with no significant effect upon the intensity and sediment production in the area. One of the main problems was the nonexistence of erosion observations in the catchment for a longer period and their comparison in time. Till now, the maps showing erosion intensity and sediment production in the catchment on the annual or seasonal level, distinguishing the areas that are more or less affected and endangered by erosion processes, do not exist. This maps make foundation for appropriate definition of erosion mitigation and protection measures and its timely implementation.

The methodology for the soil (water) erosion method selection based on Dubračina catchment has been presented and the main selection criteria chosen. Those criteria include erosion type, data availability, application scale and parameter significance each leading to a more reduced list of applicable methods. This methodology provides relatively fast and easy selection of appropriate method and can be used in similar case studies where limited amount of research and measurements was conducted in the past. Upon implementation of proposed methodology, Erosion Potential (Gavrilović) Method for the Dubračina catchment has been chosen.

The Gavrilović method is a semi-quantitative method that enables assessment of erosion coefficient (intensity), total annual sediment production and actual sediment yield. During the research on the application of the method, shown in this thesis, was noticed that the analysis using the modified formula for the sediment delivery ratio, that includes the drainage density as the ratio between the primary and secondary river length and catchment area, obtains results that correspond better to on-site measurements. From that, the recommendation to use modified formula for sediment delivery ratio in all future analysis including Gavrilović model was emphasised to avoid incorrect results indicating larger values for the actual sediment yield compared with those of the total annual volume of the detached soil.

The data included in the model are subdivided into spatially variant and spatially invariant parameters. Soil erodibility coefficient is based on soil type in the area of interest and has been pointed as one of the most important parameters in erosion models by many scientists before. Soil erodibility coefficient, with pedological map chosen as soil type primary information source, was evaluated not using the proposed tables for the Gavrilović method but instead using the nomographs for the evaluation of soil erodibility in Universal Soil Loss Equation (USLE). This procedure for the evaluation of soil erodibility coefficient has been verified and used numerous times in various methods, including USLE, and was found to be more appropriate than the proposed descriptive and numerical evaluation used in Gavrilović method. Another parameter, drainage density was analysed and derived three times using different assumptions and allowing different spatial variability of the parameter. Until today, within the Gavrilović method drainage density parameter was calculated both as a unified value for the entire catchment or as one value for each sub-catchment, restricting its spatial variability and increasing its error. The methodology used in this thesis was proposed by Dabos and Daroussin (2005) and the "actual" drainage density was calculated using the river map and not DEM derived river map as input data. Drainage density map, derived using the proposed methodology has provided a more realistic model input data with more detailed spatial variance of this parameter. Until today, there hasn`t been any research paper applying the Gavrilović method that uses this particular method for the derivation of drainage density and none uses drainage density map with spatial variability that is more than on sub-catchment level. For this reason derived map for D_d using this methodology is considered an enhancement to Gavrilović method accuracy and precision.

Till today, accordingly to research of available and published literature, parameter sensitivity analysis has not been conducted and/or published for the Gavrilović method and the parameter the method is most sensitive to have not been determined. The research shown in this thesis has included the Gavrilović method sensitivity analysis to a total of fourteen method parameters. It was concluded that the parameter with the highest sensitivity for all model outputs is the soil erodibility coefficient Y, followed by the soil protection coefficient X_a. The method sensitivity to the Average annual temperature T_0 is lower than to the Average annual precipitation P_a but, when the Average annual temperature T_0 is transformed into its related form as the Temperature coefficient T, its sensitivity is increased.

The Gavrilović model uncertainty analysis was conducted with consideration to source and time- varying input data. Source-variant parameters have shown to have a greater impact upon a model outcomes and both soil protection coefficient and soil erodibility coefficient are high sensitive model parameters all of which puts them in first ranking position as most uncertain parameters in this case study. In contrary to source-variant parameters, time-variant parameters have significantly less impact upon model and their uncertainty is related to climate change in 30-year time period. The analysis indicates that when changing the data source, significant changes to the model outcome value can occur without the awareness of an expert as to the nature of the error. Such changes are related to human error and depend on detailed preliminary research and data gathering as well as applied criteria for appropriate data selection. Various criteria can be used in the decision-making process for data selection on a case-by-case basis and some of them have been proposed and implemented in this theses.

The estimated values and maps derived by the Gavrilović model, presented in this thesis, include outputs for erosion coefficient (intensity), total annual volume of the detached soil and actual sediment yield for the past (1961 – 1990) and present time (1991 – 2020). The most noticeable spatial change in erosion coefficient between the two time series is around Slani Potok and Mala Dubračina sub-catchments, where the area affected by excessive erosion was found to increase from past to present time. The overall decrease in average values of the total annual volume of the detached soil is noted form past (15.64 m^3/cell/year) to present (15.12 m^3/cell/year) time but this change in values was not found to be significant, in contrast to the change in the spatial distribution visible on the maps.

The modification of the Gavrilović model was made in order to produce seasonal model outputs by changing three main model parameters: precipitation, soil protection coefficient and temperature. The biggest contributor to soil loss within the cycle of a year was found to be autumn (19 902 m^3/catchment/season), followed by summer (14 989 m^3/catchment/season), spring (11351 m^3/catchment/season) and at last winter (9905 m^3/catchment/season). The deviation between the annually derived values for the sediment production and overall production during the four season time period was found to be around 13%. It can be concluded that the modified Gavrilović model intended for the seasonal soil erosion assessment provides good approximation of soil erosion and can be used for future research.

Detailed analysis of the Erosion Potential Method application has shown limited number of papers describing the Gavrilović method verification process and naming the method applied. Those papers that deal with method verification have applied different verification methods depending on available equipment and accessibility of a terrain. In this thesis, the model output erosion intensity, land cover map and soil surface change was verified using visual survey monitoring method and GPS device. All verifications have given very good results and high accuracy of derived maps was confirmed.

Furthermore, soil protection coefficient, also shown with this research to be one of the parameters the method is the most sensitive to, has a large impact upon the estimated values of sediment production. It is often forgotten in erosion analysis that agricultural areas and areas with low or no vegetation cover are not the only source of eroded material. Construction sites in the regions of urban expansion has been recognized as a significant source of soil erosion sediment but were not considered with Gavrilović method till today. Construction areas, although short lived, have a substantial impact on the amount of erosion sediment production on a yearly basis. It is recommended, in this thesis, that such areas need to be taken into consideration and the numerical and descriptive evaluation of the Gavrilović method`s soil protection coefficient including the construction sites is proposed and applied. Taking into consideration potential construction sites in the Dubračina catchment the potential change in total annual volume of the detached soil that would derive form a cell 100x100m under construction was calculated. Depending of the soil type the average increase in sediment production from an area under construction is approximately 28%. Since this increase in values can cause additional problems along the catchment, erosion control measures were proposed with consideration to its economic cost. This measures should be considered in any future spatial planning in the area of Dubračina and can easily be integrated within the legal framework and acts by local government.

One of the most important prevention and mitigation measure is the removal of erosion sediment from the river bed. Until today, that has been applied approximately ones in year and a half. During the erosion monitoring in the Dubračina catchment which began in June 2014 and ended in July 2016 the riverbed was cleaned twice. First time in November 2014 and for the second time in the June 2016. Cleaning of the riverbed twice a year or at least once a year in accordance with assessed soil loss ratios within different seasons in a year, would contribute the most to those tributaries with the largest amount of sediment detached and transported downstream (Malenica, Slani Potok, Mala Dubračina).

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LIST OF FIGURES:

LIST OF TABLES:

CURRICULUM VITAE

Nevena Dragičević was born on June 20, 1984 in Rijeka. She finished elementary school in 1998 and highschool for Civil Technician in 2002. Later on she continued her education on Faculty of Civil Engineering, University of Rijeka where she graduated in 2008. Her final graduation thesis held the topic „The analysis of karst system of Plitvice lakes“ and was supervised by Assistant Professor Josip Rubinić.

Since June 2008 she has been working at the Faculty of Civil Engineering, University of Rijeka as a teaching assistant at the Division of Hydraulics and Geotechnics. While working at the university she held practical's on several different courses such as Water supply and water treatment plants, Waste management and Water management, etc.

In 2009 she enrolled in postgraduate doctoral study on the Faculty of Civil Engineering, University of Rijeka. She applied and received the scholarship „The British Scholarship Trust“ for the research entitled "Implementation of GIS technology for risk assessment of floods and erosion hazards". The research was conducted at the Lancaster Environment Centre University of Lancaster, United Kingdom in the duration of three month period in 2013 and supervised by Senior Lecturer Duncan Whyatt and Geographic Information System Officer Gemma Davies.

As a researcher she participated on the following research projects: 13.05.1.3.08 - Development of New Methodologies in Water and Soil Management in Karstic, Sensitive and Protected Areas), Croatian-Japanese project "Risk identification and Land-Use Planning for Disaster Mitigation of Landslides and Floods in Croatia", "Hydrology of Sensitive Water Resources in Karst" (114-0982709-2549) and Networking for Drinking Water Supply in the Adriatic Region (DRINKADRIA).

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